JPL PUBLICATION 85-58

Second-Generation Mobile Satellite System

A Conceptual Design and Trade-Off Study

M.K. Sue
Y.H. Park

June 1, 1985

NASA

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Jet Propulsion Laboratory
California Institute of Technology

4800 Oak Grove Drive
Pasadena California 91109

(818) 354-4321

JPL

September 27, 1985

NASA Scientific and Technical
Information Facility
P.O. Box 8757
Baltimore-Washington International Airport
Maryland 21240

Attn: NASA Representative (S-AK-RKT)

Gentlemen:

Enclosed is a list of JPL Publications released during August 1985. For each listed publication we are also enclosing a COSATI Standard Title Page and two copies of the document.

Very truly yours,

Linda Worrel

Linda Worrel
Document Review Group
Documentation Section

LW:dk
Enclosures
cc: P. French
Acquisitions Branch
(with copy of list)

JPL PUBLICATION 85-58

Second-Generation Mobile Satellite System

A Conceptual Design and Trade-Off Study

M.K. Sue
Y.H. Park

June 1, 1985

NASA
National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

CONTRIBUTORS

The following individuals made significant contributions in the noted areas:

R. G. Chamberlain -- User Cost Model

R. E. Freeland -- Deployable Antenna Study

V. Jamnejad -- Antenna/Feed Design and Trade-offs

-- Satellite Mapping, Multibeam Coverage, and Interbeam Isolation Study

E. K. Smith -- Propagation in the Mobile-Satellite Communications Environment

C. Wang -- Second-Generation Mobile-Satellite Networking Concept

T. Y. Yan -- Second-Generation Mobile-Satellite Networking Concept

PRECEDING PAGE BLANK NOT FILMED

ACKNOWLEDGMENTS

This study would not have been completed without the help of many individuals at various aerospace companies. The information on the high-power communications satellites, upon which our study is based, is in part derived from data provided to us by the Hughes Aircraft Company, Ford Aerospace and Communications Corp., and RCA Astro-Electronics. The spacecraft design is based on studies performed by Ford Aerospace and Communications Corp. and RCA Astro-Electronics, under contracts to JPL. The information on the deployable antenna is derived from data provided by Lockheed Missiles and Space Company, Inc. and the Harris Corporation, also under contracts to JPL.

At JPL, we owe our thanks to many colleagues. In particular, we would like to thank Mr. D. J. Bell, Drs. J. Huang, Y. H. Lin, F. Naderi, and W. J. Weber, III for their useful input and suggestions. We would also like to express appreciation to Mr. R. A. Harrington and Mr. C. T. Westfall for running the computer program to generate the cost estimates used in the report. Last, but not least, we thank Mrs. Barbara Vaughn for her patience and diligence in typing this document.

PREFACE

In recent years, interest has grown in the mobile satellite (MSAT) system, a satellite-based communications system capable of providing integrated voice and data services to a large number of users. The FCC has issued a Notice of Proposed Rulemaking (NPRM) for a frequency allocation for the Mobile Satellite Service and 12 companies have filed applications for a license to launch the so-called first-generation MSAT within the next 5 years.

To maintain the U.S. leadership in space, NASA is interested in accelerating the development of a commercial mobile satellite system (MSS) and technologically enhancing the future MSAT generations. To accomplish these goals, NASA has structured a three-phase Mobile Satellite Program to develop ground and space segment technologies. The first phase, called the Mobile Satellite Experiment or MSAT-X, is developing advanced ground segment technologies and will demonstrate these technologies using the first commercial MSS. Phase 2 of the NASA program will develop and flight test on the Shuttle the large multi-beam spacecraft antenna technology needed to obtain substantial frequency reuse for second-generation commercial systems. Phase 3 is similar to Phase 2 except that NASA will develop an even larger antenna and test it in conjunction with the Space Station.

To explore the potential of the MSS beyond the horizon of the first generation, using technologies of the 1990's, and to direct the technological objectives of the NASA MSS Program, a conceptual design has been performed for a second-generation system to be launched around the mid-1990's. The design goal is to maximize the number of satellite channels and/or mimimize the overall life-cycle cost, subject to

the constraint of utilizing a commercial satellite bus with minimum modifications. To provide an optimal design, a series of trade-offs was performed, including antenna sizing, feed configurations, and interference analysis. In addition, a costing model was developed to assist in assessing the financial merits of various technological approaches.

While the study presented in this report is based on a hypothetical frequency allocation in the UHF band, a system that operates at L-band, an alternative frequency band that is being considered by some for possible future MSAT applications, is also presented.

TABLE OF CONTENTS

Table of Contents (Continued)

PART TWO

Table of Contents (Continued)

Table of Contents (Continued)

Table of Contents (Continued)

Table of Contents (Continued)

Table of Contents (Continued)

Table of Contents (Continued)

Table of Contents (Continued)

APPENDICES

FIGURES

Table of Contents (continued)

Table of Contents (continued)

Table of Contents (continued)

Table of Contents (continued)

Table of Contents (continued)

Table of Contents (continued)

Table of Contents (continued)

TABLES

Table of Contents (continued)

Table of Contents (continued)

PART ONE

EXECUTIVE SUMMARY

1.0 INTRODUCTION

A mobile satellite (MSAT) system consists of a space segment and a ground segment. The space segment contains one or more satellites in the geostationary orbit. The ground segment primarily is made up of gateway stations, network management centers (NMC), and mobile terminals. Figure 1 illustrates a typical mobile satellite network and its elements. The space segment and the ground segment together form a communications network that allows mobile users anywhere in the coverage area to communicate. A mobile satellite system can perform many functions, such as mobile telephone, radio dispatch, position location and surveillance, and emergency communication for disaster relief. Its usage is limited only by one's imagination.

The operation of the mobile satellite network is very similar to the terrestrial mobile phone system. The geostationary satellites function as relay towers, and the NMC is the brain of the network, controlling the operation of the network by monitoring the traffic and assigning channels. The gateway station provides an interface between the mobile satellite network and other networks, such as the Public Switched Telephone Network (PSTN), enabling the mobile satellite system users to communicate with users in other networks. Much interest has been generated in recent years in the mobile satellite service. A Notice of Proposed Rulemaking (NPRM) has been issued by the Federal Communications Commission (FCC) for a frequency allocation for this service, and 12 companies have applied for a license to launch a first-generation mobile satellite system. In a few years, there will be a system providing mobile services to thousands of users.

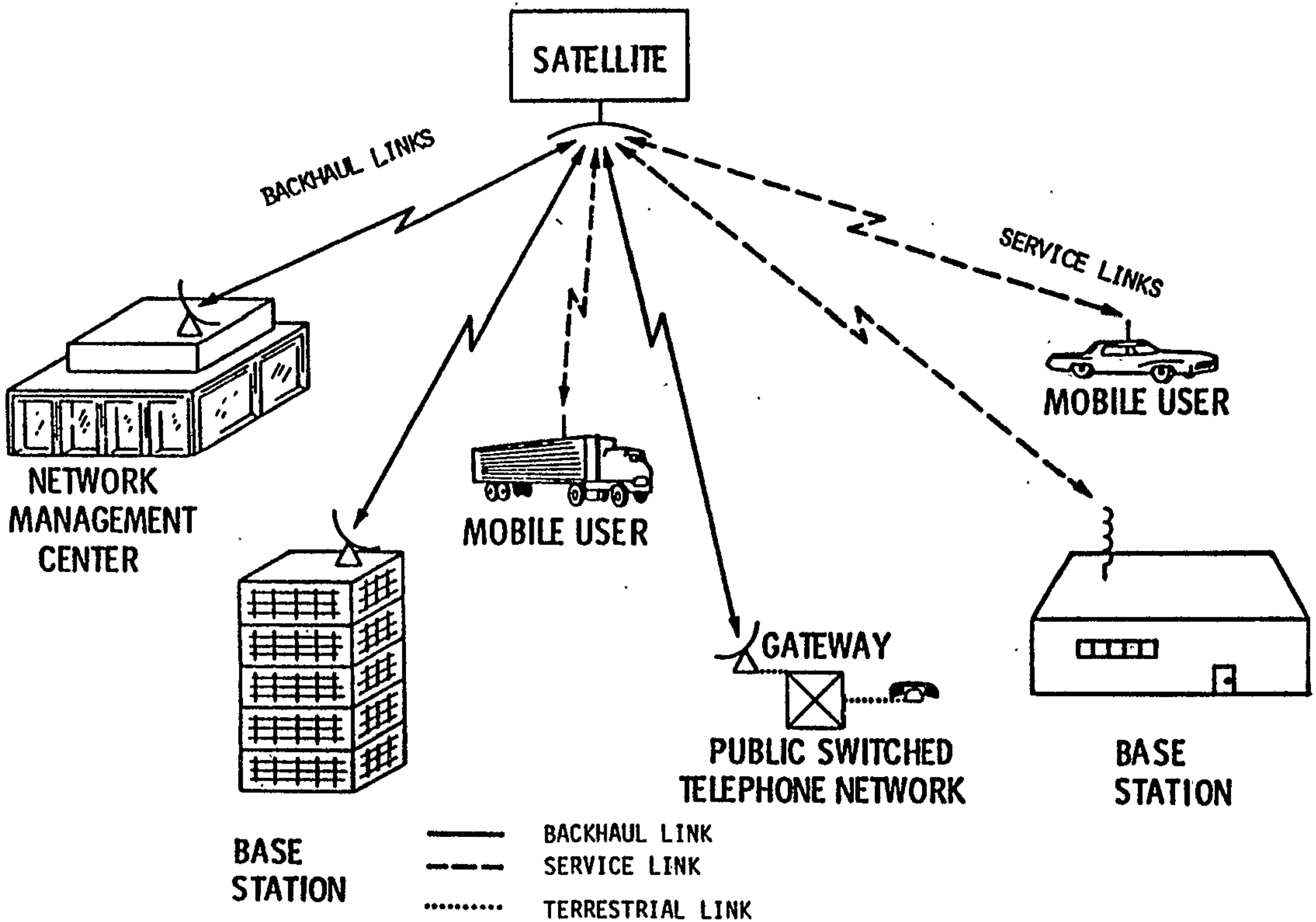


Figure 1. A Mobile Satellite Network

Because of the start-up cost, the first-generation system, which is expected to be in operation in the late 1980's to the early 1990's, will probably have a very limited capacity. In anticipation of future growth, a system with greater capacity will be needed and is expected to begin operations around the mid-1990's. This system is referred to as the second-generation mobile satellite system (MSAT-2) and was the subject of this study.

The objectives and the ground rules of this study are described in Sections 1.1 and 1.2. The results of the study are summarized in Sections 2 through 3. Section 4 identifies future studies needed to ensure the timely development of MSAT-2.

1.1 STUDY OBJECTIVES

The primary objectives of this study were as follows:

(1) To perform a conceptual design of a second-generation mobile satellite system operating at the UHF frequencies in the late 1990's to the early 2000's.

(2) To examine various parametric trade-offs to produce a cost-effective design and to aid MSAT-X and other NASA MSS technology programs setting development priorities.

(3) To examine an alternative system operating at the L-band frequencies.

(MSAT-X is a NASA-funded program. Its objectives are to develop advanced ground-segment technologies and techniques for use in future mobile satellite systems, and to verify these technologies using the first-generation mobile satellite system.)

The secondary objectives of the study were to analyze the sensitivity of the system's capacity and user cost to different variables including, but not limited to, the following:

1) Bandwidth allocation, i.e., 4-MHz versus 10-MHz allocations
2) Mobile antenna design, i.e., low-gain antenna (LGA) versus medium-gain antenna (MGA).

1.2 GROUND RULES

To limit the scope of the study and to efficiently use the available resources, a number of assumptions, ranging from the system level to the subsystem level, were made in the study. These assumptions are based on the work performed by MSAT-X, the best available information, or the best estimates. The specific assumptions are given in the following sections.

1.2.1 Service Area

It was assumed that MSAT-2 will be required to provide services to the contiguous United States (CONUS), Alaska, and Canada.

1.2.2 Operating Time-Frame and Technology

It was assumed that MSAT-2 will be launched around the mid-1990's and the satellites will be designed using 1990 technology, thus benefitting from future technology improvements. The satellite bus will be a modified commercial bus. One of the design goals was to minimize the extent of modifications.

1.2.3 Multiple Access Scheme

The system will employ a single channel per carrier (SCPC), frequency division multiplexing (FDM), and demand assignment multiple access scheme (DAMA), or simply SCPC-FDM-DAMA.

1.2.4 Baseband Modulation, Data Rate, and Channel Spacing

The modulation/demodulation methods suitable for MSAT must meet several stringent requirements. They must be (1) bandwidth efficient, (2) power efficient, and (3) robust in the mobile environment. Various baseband modulation/demodulation schemes have been investigated by MSAT-X for MSAT applications. At present, digital modulation using Gaussian baseband filter minimum-shift-keying (GMSK) is considered to have the potential to meet the requirements and is being studied extensively by MSAT-X. The baseband modulation for MSAT-2 was assumed to be GMSK with either a coherent or differential detection.

MSAT-2 will be designed to provide both voice and data services. The analog voice will be digitized using a linear predictive coding (LPC). With a bandwidth-efficient modulation, 2400 bps will be supported using a 5-kHz channel.

1.2.5 Operating Frequencies

Two systems were examined: a baseline system and an alternative system. Each system requires two frequency assignments, one for the service links and one for the backhaul links. The service links are between the satellite and the mobile terminals, and the backhaul links are those between the satellites and

the gateway stations, the base stations, or the NMC (Figure 1). For the baseline system, the service links were assumed to be operating in the high UHF, and the backhaul links in the Ku-band. The available UHF bandwidth was assumed to be a pair of bands of 10-MHz each, with 10-MHz for uplink and 10-MHz for downlink, as shown in Figure 2. The assumed backhaul frequency is 13.2 GHz and 11.65 GHz for uplink and downlink, respectively. The assumed bandwidth is 50 MHz for uplink and 50 MHz for downlink.

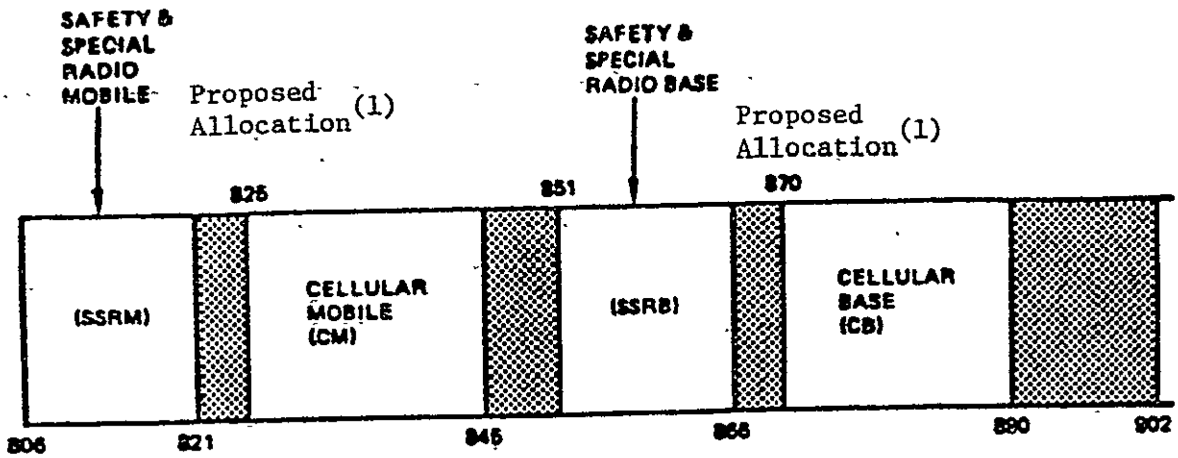
The backhaul frequency for the alternative system (L-band) was assumed to be the same as for the UHF system. The service link frequency was assumed to consist of a pair of 10-MHz bands in the band currently allocated for the Aeronautical Mobile Service, which is 1646.5 to 1666 MHz for uplink and 1545 to 1559 MHz for downlink.

1.2.6 Mobile Antenna

Similar to the modulation/demodulation scheme, the design requirements for the mobile antenna are very stringent. In addition to providing the needed gain to ease the burden on the satellite, a mobile antenna must be low cost and low profile and must provide adequate discrimination against multipath and adjacent satellite interference.

Various antennas have been investigated for mobile applications: LGA, MGA, and high-gain antenna (HGA). Three MGA concepts have been extensively investigated by MSAT-X: 1) the non-conformal mechanically steered antenna, 2) the conformal mechanically steered antenna, and 3) the electronically scanned conformal array. For MSAT-2, the non-conformal mechanically steered antenna, which is also referred as the 1 x 4 tilted array, was selected as the baseline antenna.

a)



(1) In a Notice of Proposed Rulemaking released January 28, 1985, the FCC proposed to allocate on a primary basis the 821 to 825 MHz and 866 to 870 MHz for MSS.

RESERVE

b)

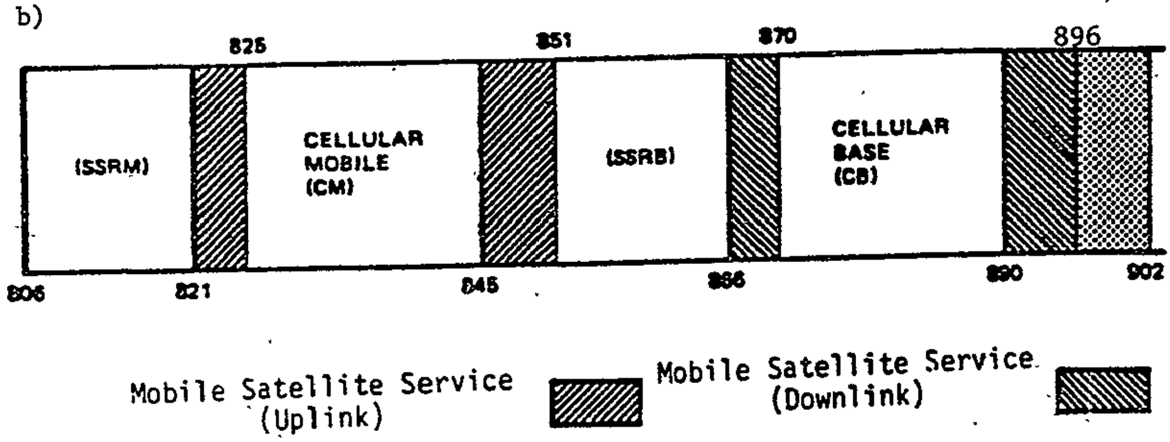


Figure 2. MSAT-2 Study: a) Current FCC Frequency Allocation in the 806 to 902 MHz Band and b) Assumed Allocation

2.0 UHF SYSTEM

The baseline system is designed to provide services to CONUS, Alaska, and Canada. Two geostationary satellites at 90 and 130 degrees west longitude will accommodate hundreds of thousands of users at a reasonable cost. MSAT-2 will provide a capacity of about 9000 channels, which is far greater than that of the first-generation system. The large capacity is obtained by employing a moderately large deployable antenna with a 20-m diameter, by using a high-power bus, and by relaxing the north-south station-keeping requirement to ± 2 degrees and the eclipse capability to 50%. The large capacity necessitates an efficient frequency utilization. A frequency reuse of up to 4 times is achieved by employing multibeam technology and a frequency reuse scheme with a reuse factor of 7. (The frequency reuse factor is simply the number of frequency subbands into which the available frequency band is divided. The subbands are then assigned to different spot beams with some or all of the subbands being assigned to more than one beam to achieve frequency reuse.)

Interbeam interference is generally a serious problem in an environment using multibeam and frequency reuse. In the mobile satellite environment, the interference problem is further exacerbated by the presence of multipath fading. To abate interference, an overlapping feed is often suggested because the resulting beam's sidelobe level is generally lower than that for a non-overlapping feed. The overlapping feed and the associated beam-forming network (BFN), however, are heavy and complex. Based on results of a series of trade-off studies and a detailed interference analysis, a non-overlapping feed is proposed for MSAT-2. Avoiding the need for a heavy and complicated BFN results in an increase in satellite channels.

The relatively simple technology employed by MSAT-2, and the system's large capacity, make the system economically viable. Although a large amount of capital would be required, the system appears to be an attractive investment due to a low user monthly cost. The cost of the space segment is estimated to be $500M in 1985 dollars, including $276M for the three satellites (2 active and 1 hot spare), $165M for launch, and $60M for insurance. Because of the large capacity, the estimated user cost is about $0.20 per call-minute. For a user having a low-cost mobile terminal equipped with a non-conformal mechanical MGA, the monthly cost is about $65 for 100 call-minutes. For users having a conformal mechnical antenna or an electronically phased array, the monthly cost would be $10 to $20 higher, respectively. (The above charge rate is for one-way (simplex) communications. For two-way links (duplex) the charge rate should be doubled. For convenience, all future discussions on charge rates and monthly usage (in call-minutes) will be based on one-way links unless explicitly stated otherwise.)

The salient features of the UHF system are summarized in Table 1. The mass budget is shown in Table 2. The block diagram of the transponder is given in Figure 3. The MSAT-2 design represents the result of a series of trade-off studies. The key trade-offs and the characteristics and design of major components are summarized in the following sections.

2.1 THE MSAT-2 BUS

The design goals are to maximize the number of satellite channels and to minimize the user cost, subject to the constraint of the capability of commercial satellite buses. A survey of satellite manufacturers indicates that the class of high-power communications satellites currently being developed or already in

Table 1. Salient Features of the Baseline Design

Number of Satellites	2
Service Link Frequency	UHF
Backhaul Frequency	Ku
Number of Multiple Beams (UHF)	24 (East Sat.) 21 (West Sat.)
Number of Beams (Ku)	1
Antenna Size (Service Links)	20 m
Spacecraft Weight at GTO	2800 kg (6200 lbs)
Total Number of Satellite Channels	9000
Number of Users(1)	900,000
Eclipse Capability	50%
North-South Station-Keeping Capability	± 2 degrees
Frequency Utilization	Up to 4 times
Estimated Charge Rate	$0.20 per call-minute
Estimated User Monthly Cost(2)	$65.00

Notes:

(1) Based on a voice-to-data user mixture of 1 to 5.

(2) Based on 100 call-minutes per month (one-way).

Table 2. Mass Summary

	East Satellite kg	(West)
Communication Payload	490	(458)
TT & C	24	
ACS	70	
Propulsion	141	
Power	221	
Structure	156	
Thermal	36	
Electrical Integration	51	
Mechanical Integration	15	
Margin	135	(167)
Dry weight	1339	(1339)
Station-Keeping Fuel	234	
BOL Weight	1573	(1573)
Apogee Propellant	1269	
GTO Mass	2842	(2842)
Cargo Mass	8600	(8600)

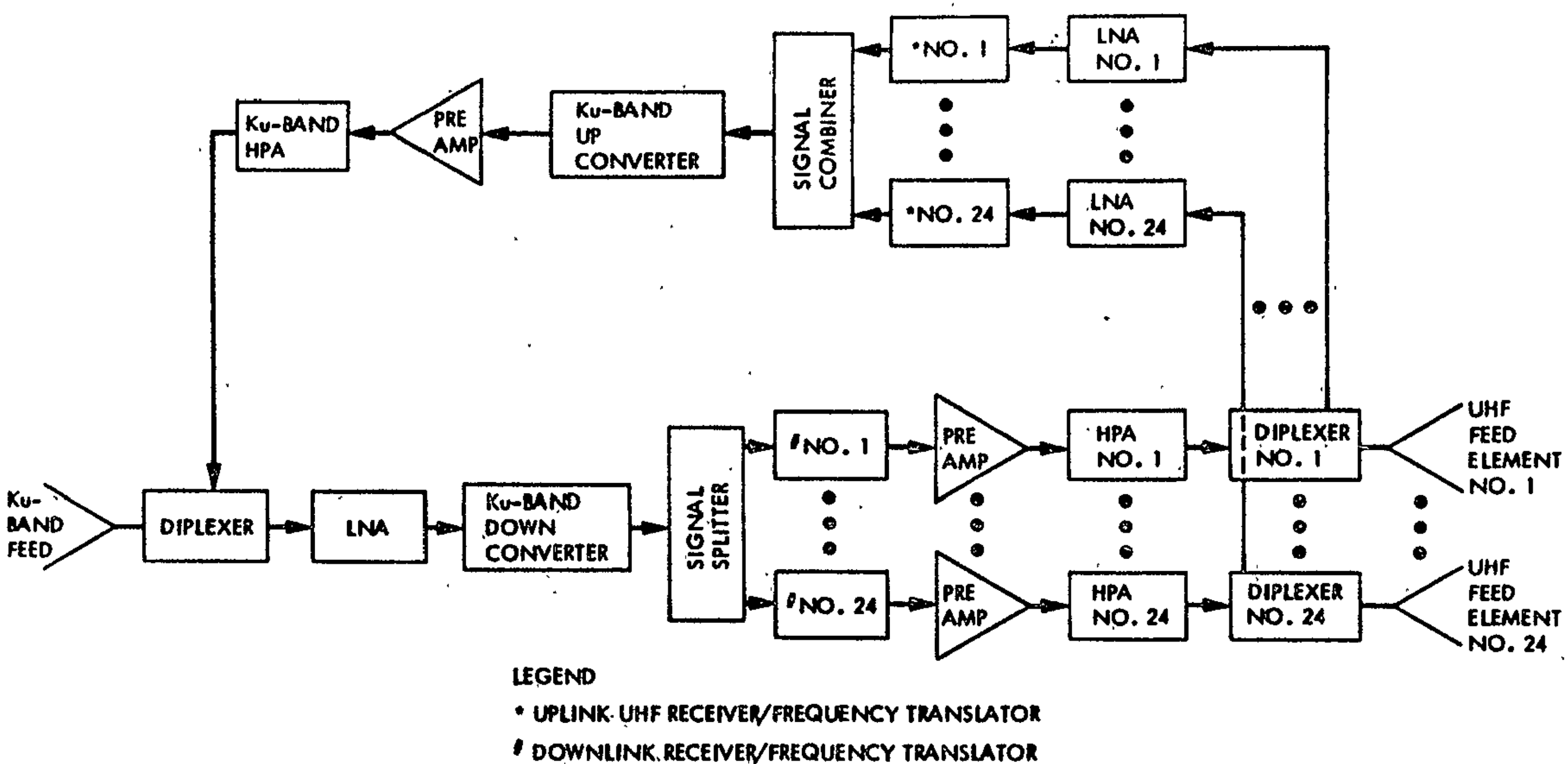


Figure 3. A Simplified Transponder Block Diagram [East Satellite]

existence would be applicable for MSAT-2. This class of satellite is STS compatible and weighs up to 2800 kg in the geostationary transfer orbit (GTO). This class of bus is capable of supporting an approximate payload weight of up to 500 kg or a payload power of up to 4 kW. The advertized or projected capability of this class of satellite varies over a range due to different designs, possible deviations, or future improvements. The range of the capabilities in terms of the weight and power of the communications payload is shown in Figure 4. The nominal capability will be selected for MSAT-2 and will form the basis for subsequent design/trade-offs.

2.2 NUMBER OF SATELLITES AND THEIR LOCATIONS

MSAT-2 employs two satellites at 90 and 130 degrees west longitude. In selecting the number of satellites, consideration was given to the projected market demands, the estimated capacity of the satellites, and the advantages of a two-satellite system over a one-satellite system. Those advantages include the added reliability of overlapping coverage, an additional service, (i.e., position location), and the larger total capacity of the system.

The selection of the satellite location was primarily influenced by the coverage requirement, the required elevation angle, and the ability of the mobile antenna to discriminate between adjacent satellites. The chosen locations provide 40 degrees of separation, sufficient for most mobile antennas. A map showing the contour of the 10-degree elevation angle for the east and west satellites is given in Figs. 5 and 6. As evidenced in these figures, good coverage is provided for the entire CONUS, and most of Alaska and Canada. Reliable service for a lower elevation angle is difficult to maintain due to the loss or

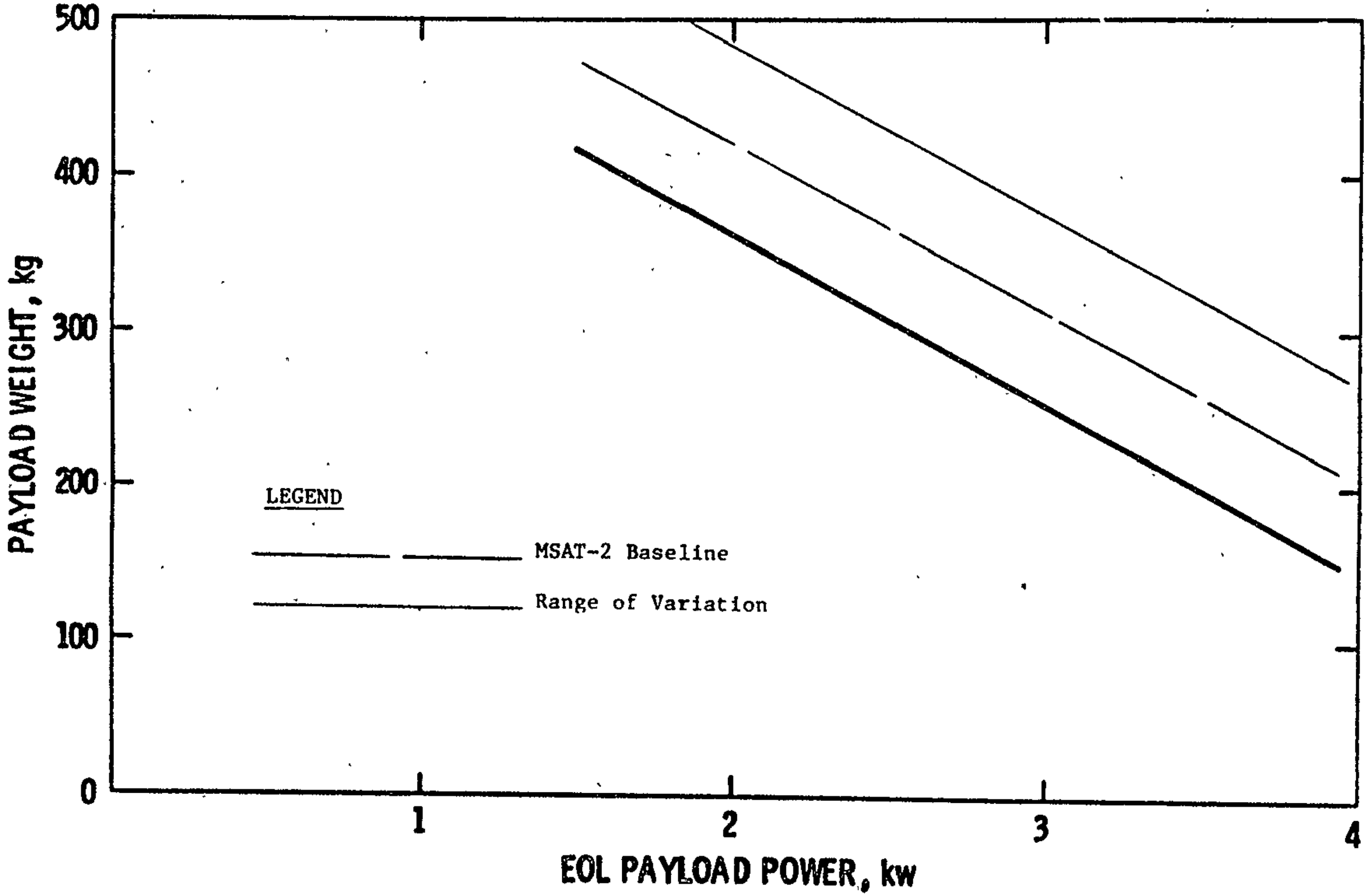


Figure 4. MSAT-2 Baseline Payload Weight Versus Payload Power

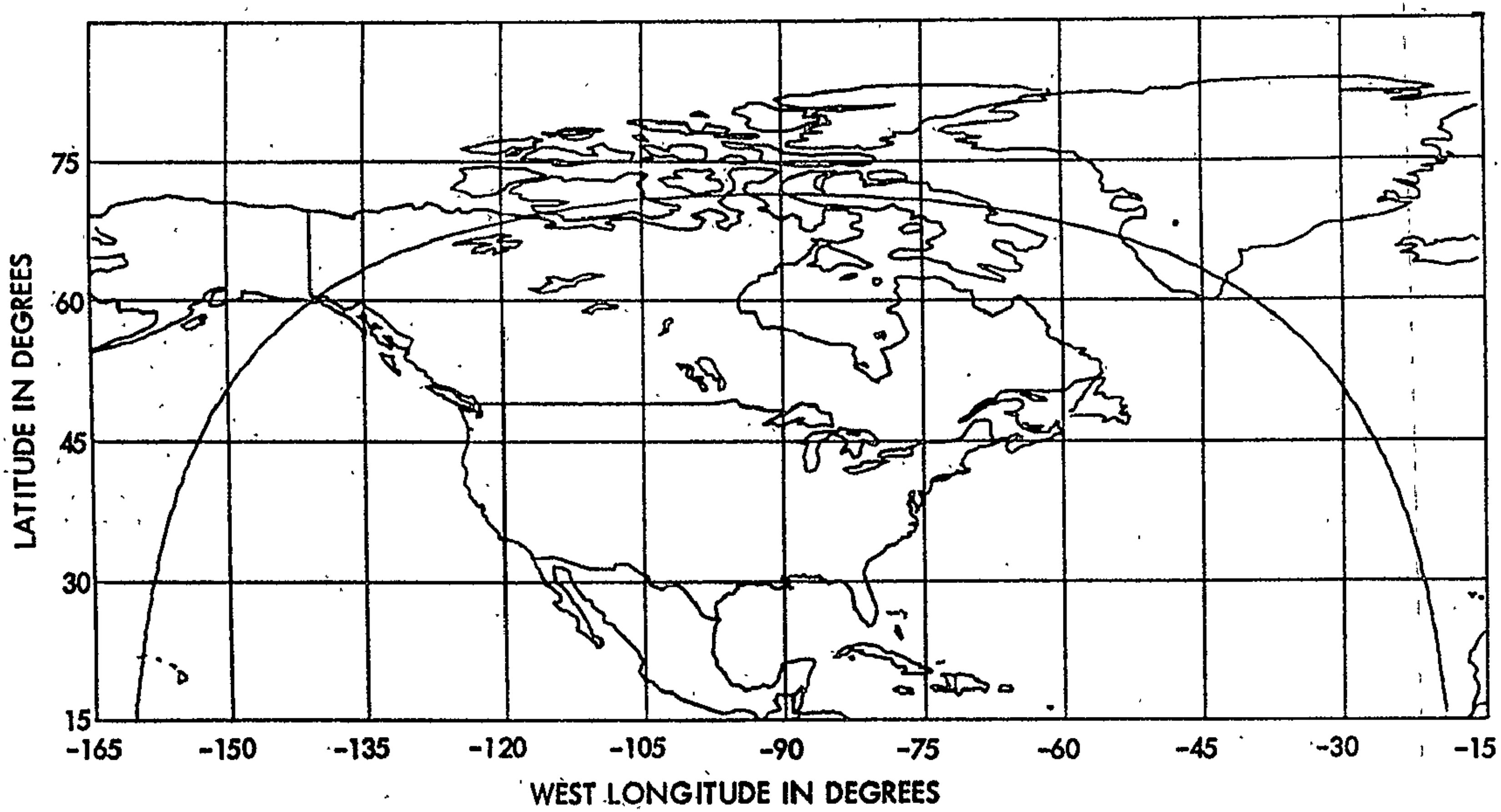


Figure 5. Contour of 10-Degree Elevation Angle for a Satellite at 90 Degrees West

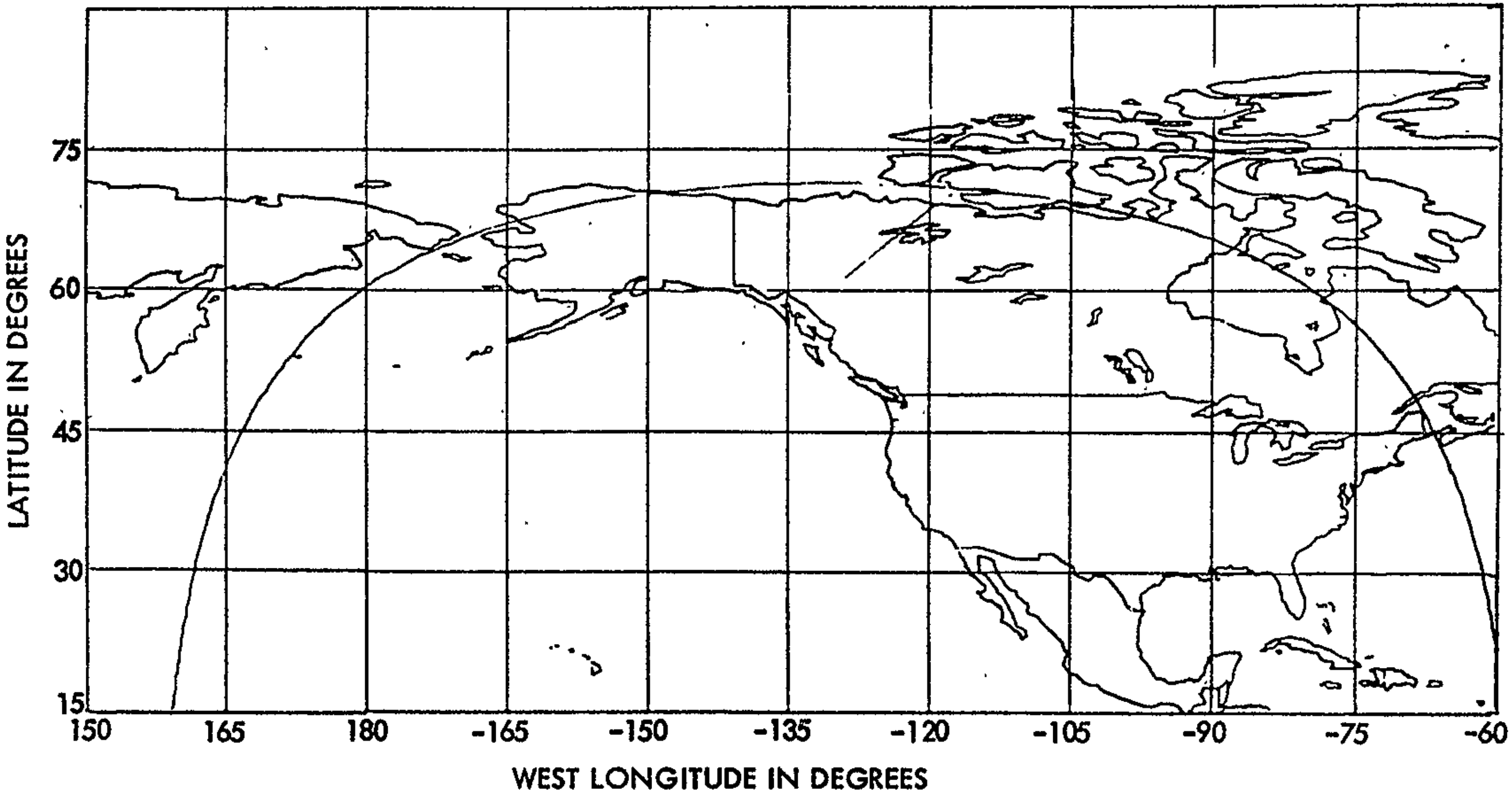


Figure 6. Contour of 10-Degree Elevation Angle for a Satellite at 130 Degrees West

blockage of the line of sight and multipath fading, but reasonably good service can be obtained for elevation angles above 10 degrees.

2.3 SPACECRAFT CONFIGURATIONS

Perhaps the most prominent feature of the satellite is the 20-m deployable antenna. The configuration of the spacecraft in both the stowed and deployed positions is primarily determined by the antenna configuration. Various spacecraft and antenna configurations were examined. Maintaining a low sidelobe level and minimizing the gain loss dictate an unblocked aperture, which in turn call for an offset-fed antenna configuration. In light of these requirements and their impact on the attitude control subsystem, two spacecraft configurations have been identified as possible candidates. The spacecraft is shown in the deployed and stowed positions, respectively, in Figs. 7, 8, and 9 for configuration 1, and in Figs. 10 and 11 for configuration 2.

The approximate dimensions of the deployed spacecraft are 25 m (82 ft) in the east/west direction, 20 m (65 ft) in the north/south direction, and 25 m (82 ft) in the earth/anti-earth direction. Because of the large reflector, the spacecraft will have to be launched in the horizontal position. The stowed dimensions are roughly 4.6 m (15 ft) in diameter and 7.2 to 8.8 m (24 to 29 ft) in length.

The large dimensions of the deployed spacecraft present a challenge to the design of the attitude control subsystem. Recent preliminary studies performed in connection with the MSAT-2 study have found no major technical design problems and extensive modifications of existing designs are not anticipated.

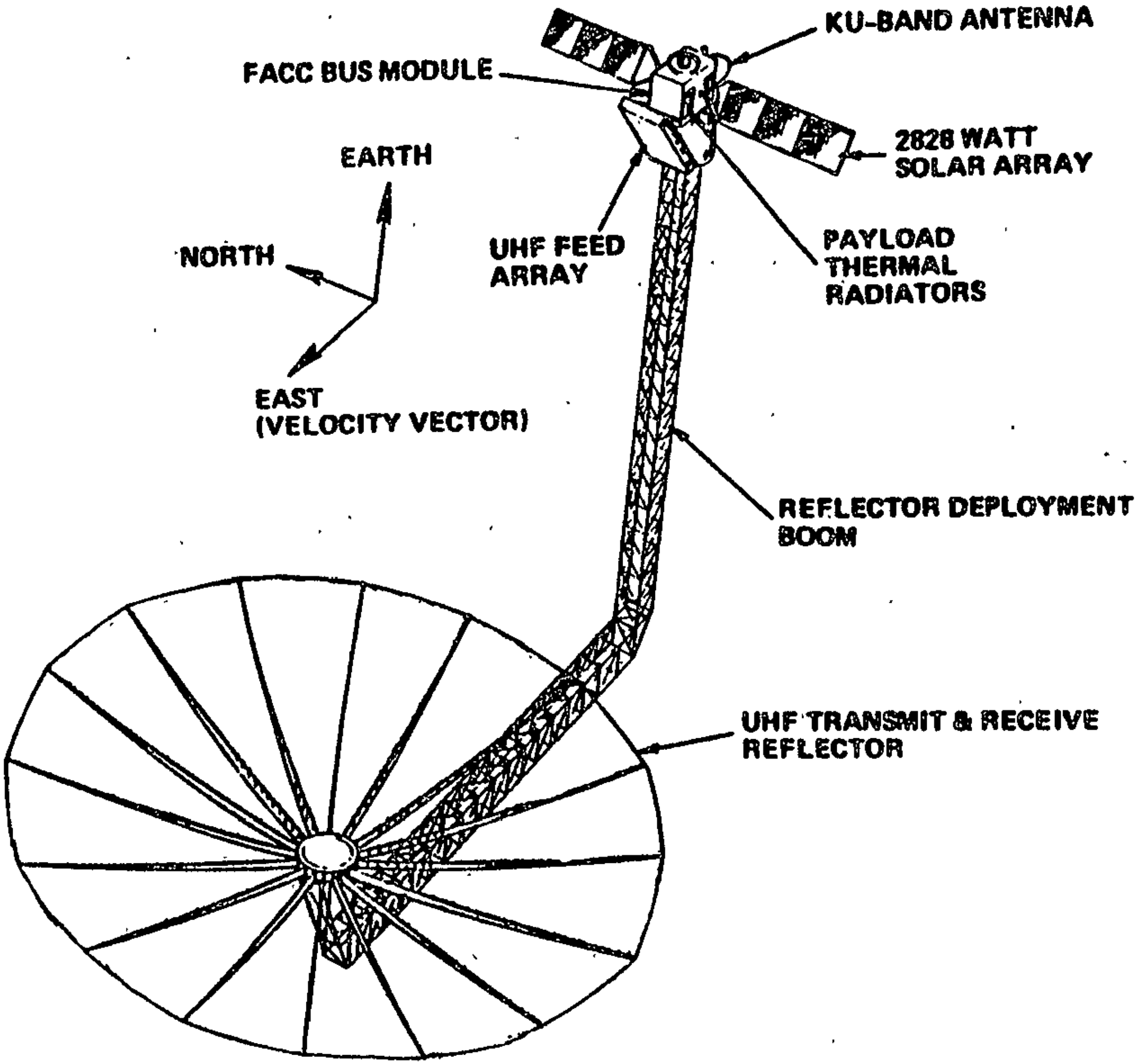


Figure 7. A Perspective Sketch of the Spacecraft (Configuration 1)

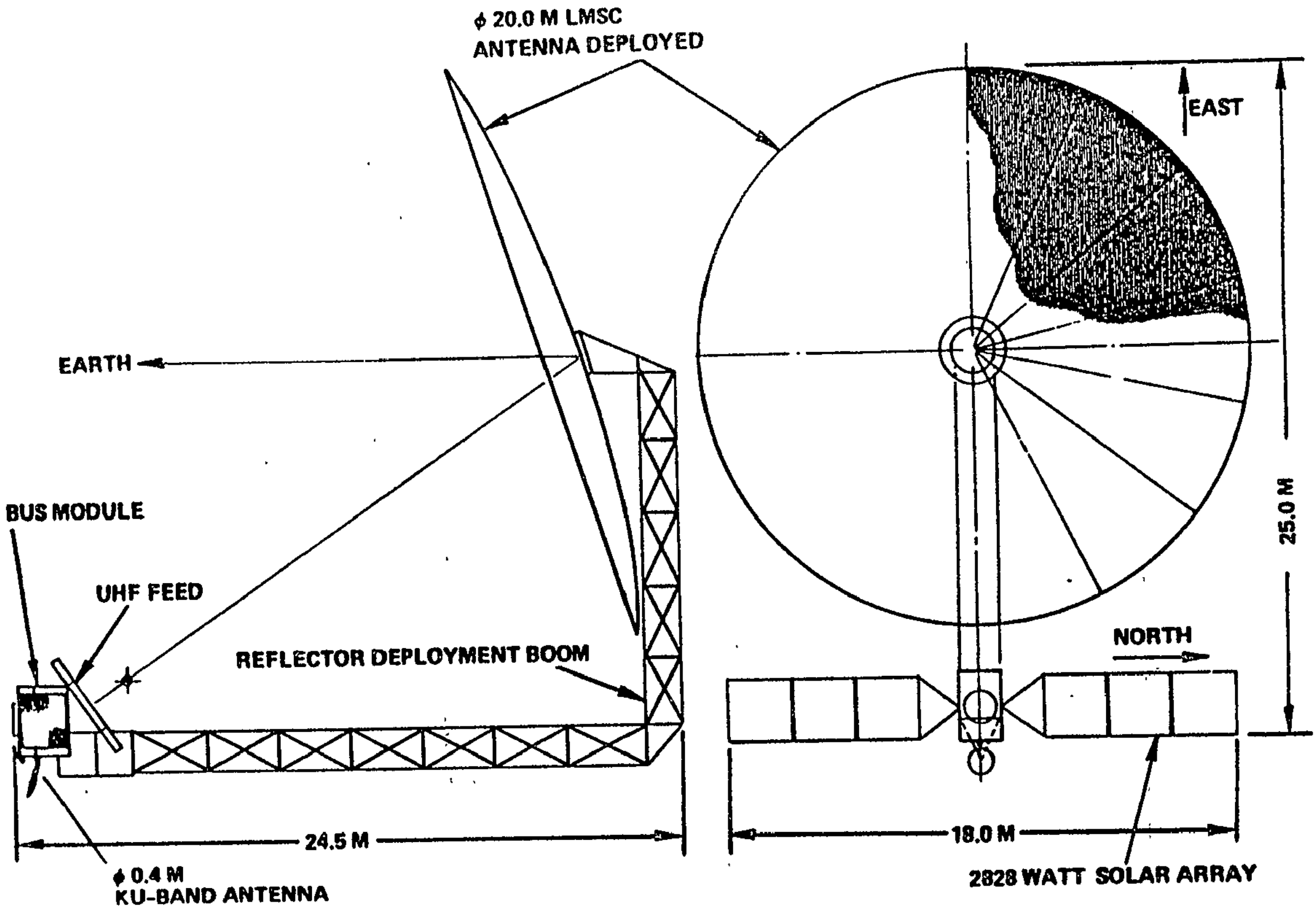


Figure 8. Deployed Configuration (Configuration 1)

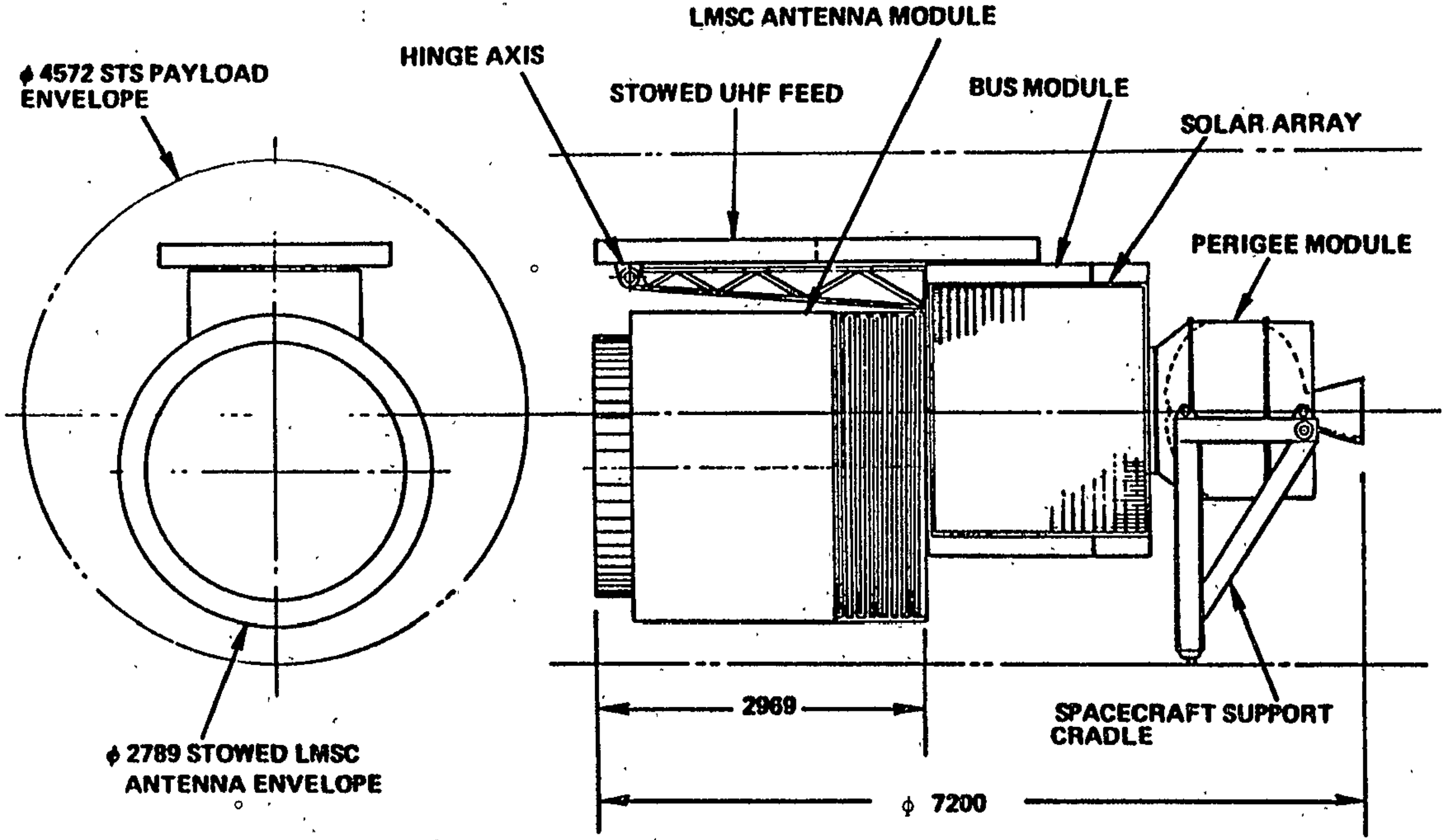


Figure 9. The Stowed Configuration (Configuration 1)

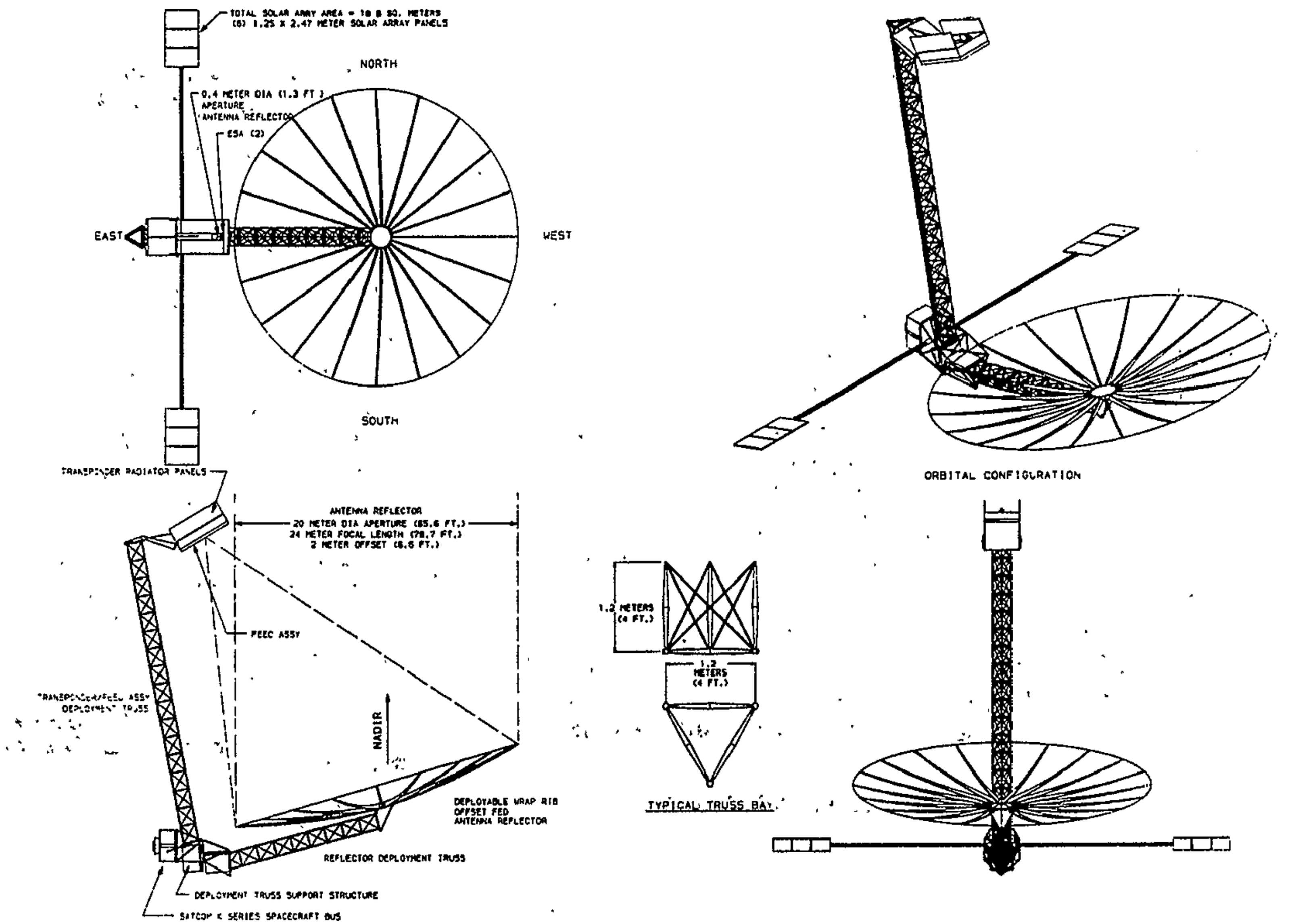


Figure 10. On-Orbit Configuration (Configuration 2)

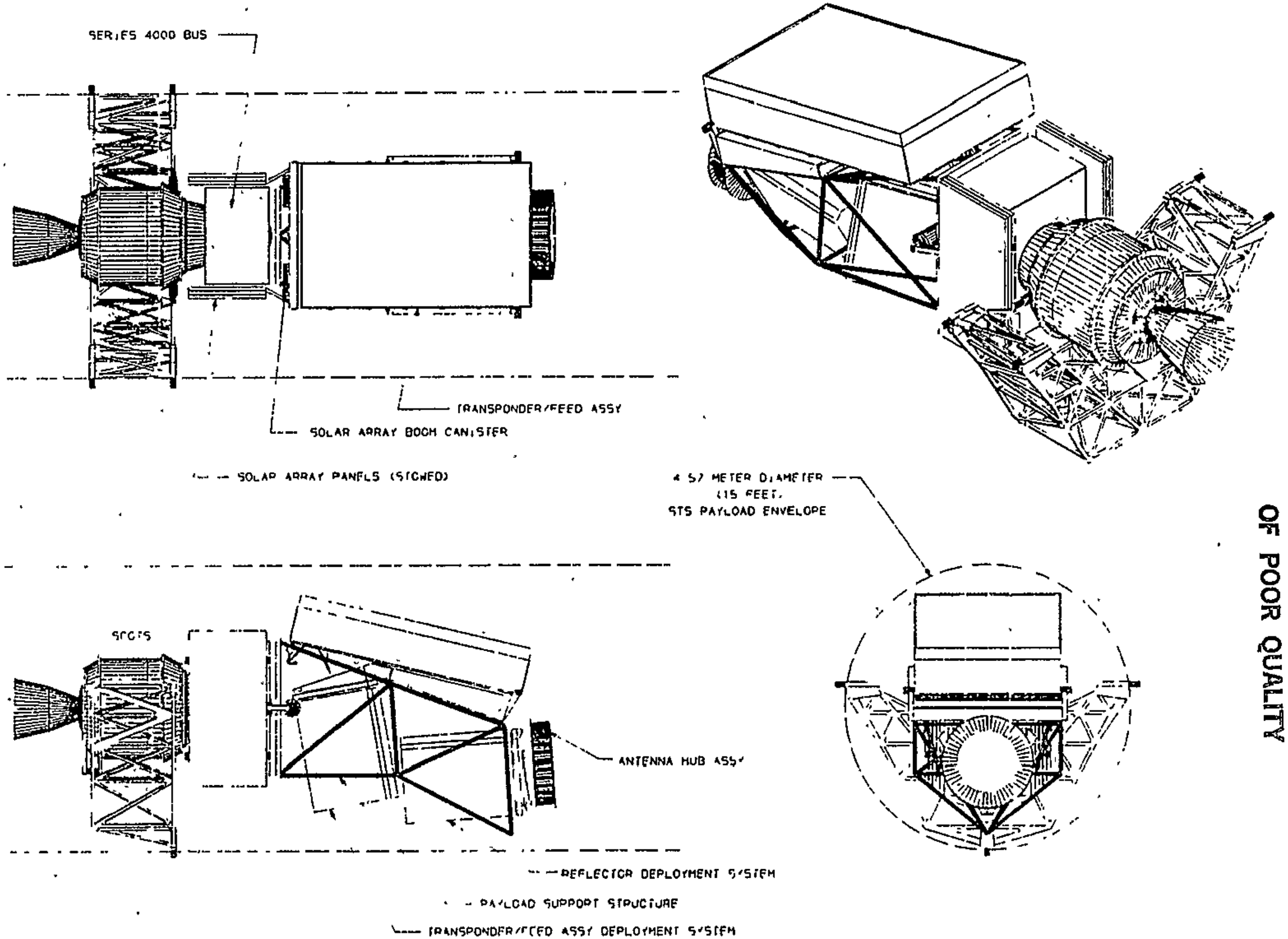


Figure 11. The Stowed Configuration (Configuration 2)

2.4 ANTENNA CONCEPT, ANTENNA SIZE, AND DESIGN

The antenna has a significant impact on MSAT-2 in terms of the weight, cost, and capacity of the system. A lot of effort has been devoted to the selection of the antenna concept, size, and design.

2.4.1 Antenna Concept

MSAT-2 calls for a fairly large antenna to alleviate the burden on the mobile terminals and the satellite power subsystem, to provide a large number of channels, and to generate a reasonable number of spot beams for efficient utilization of the spectrum. Flying a large antenna requires a self-deployable space structure and an efficient mechanical package. An examination of deployable antenna concepts has identified the Lockheed wrap-rib deployable antenna as a candidate. Limited resources for this study precluded detailed examination of other concepts. The selection of the wrap-rib antenna is solely for the purpose of this study and does not exclude others for possible MSAT-2 applications. Figure 12 shows the wrap-rib deployment scheme.

2.4.2 Antenna Sizing

The size of the antenna is driven, on one hand, by the desire to maximize the number of satellite channels and frequency reuse, and is constrained, on the other hand, by the STS stowage requirement and by the controllability of the resulting spacecraft. Three sizes (25-, 20-, and 15-m) have been examined and the results can be summarized as follows:

1) A 25-m antenna would result in a payload exceeding the capability of the baseline bus

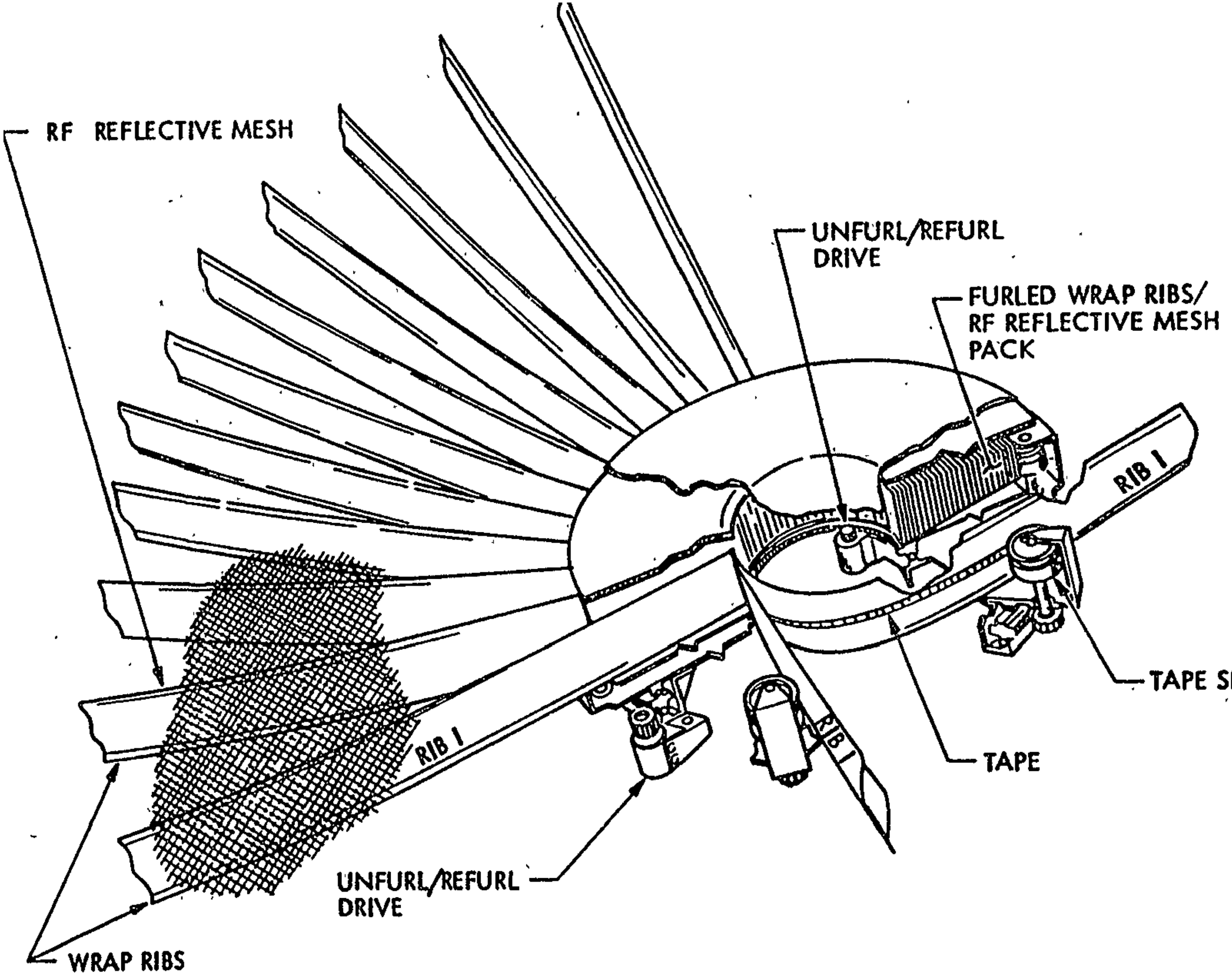


Figure 12. Wrap-Rib Antenna Deployment Scheme

2) A 15-m antenna would offer substantially fewer channels and would have a higher user cost than a 20-m antenna. In addition, the capacity of a 15-m antenna could become severely frequency limited if the available frequency band is less than 10 MHz.

Based on the above conclusions, a 20-m antenna was deemed appropriate.

2.4.3 Design of the 20-m Antenna

The antenna reflector is an offset-fed deployable parabolic-shaped reflector with a deployed diameter of 20 meters. The wrap-rib reflector consists of a central hub and deployment mechanism, 20 lenticular-cross-section parabolic ribs, and a gold-plated, light-weight molybdenum-wire mesh (Figure 12). The estimated surface accuracy of this reflector exceeds the requirement of 1/50 of a wavelength.

The antenna or feed supporting mast is a deployable structure consisting of a 20-m (65-ft) parallel segment and a 10-m (33-ft) offset segment. The mast is designed to provide a focal-length-to-antenna diameter ratio (F/D) of 1.0. The mast design, although not optimized, enables the spacecraft to be stowed in the STS cargo bay.

2.4.4 Feed Design and Beam Layout

The feed configuration trade-off is complicated because it affects the interbeam isolation and the payload weight, both of which in turn affect the number of satellite channels. To further complicate the trade-off, the interbeam isolation varies as a function of the frequency reuse factor and the antenna

size. Various combinations of antenna size, frequency reuse, and feed designs, including 1-, 4-, and 6-element feeds, have been studied and the resulting interbeam isolation, payload weight, and the number of channels have been estimated. Based on the criterion of maximizing the satellite channels, the single-feed design and the 7-frequency reuse scheme are proposed. The use of a non-overlapping feed avoids the need for a heavy and complicated BFN and consequently increases the system capacity.

A beam layout and the frequency subband assignments for a 7-frequency reuse scheme are shown in Figures 13 and 14 for the east and west satellites, respectively. As indicated, some of the subbands are being reused as many as four times in order to obtain the large number of channels.

3.0 L-BAND SYSTEM

To anticipate a possible future frequency allocation in the L-band and to recognize the congestion in the UHF spectrum, an alternative system, operating at the L-band frequencies, has been studied. The goal of the L-band study is to assess its capacity and its cost relative to the UHF system (under the same general ground rules).

The design and operation of the L-band system are generally the same as the UHF system with the exceptions of the antenna size (for the service links) and the resulting system capacity. The UHF system calls for a fairly large deployable antenna (20 m). Using the same baseline bus, it is estimated that the proper size for an L-band system is roughly between 10 and 15 m. A system using an

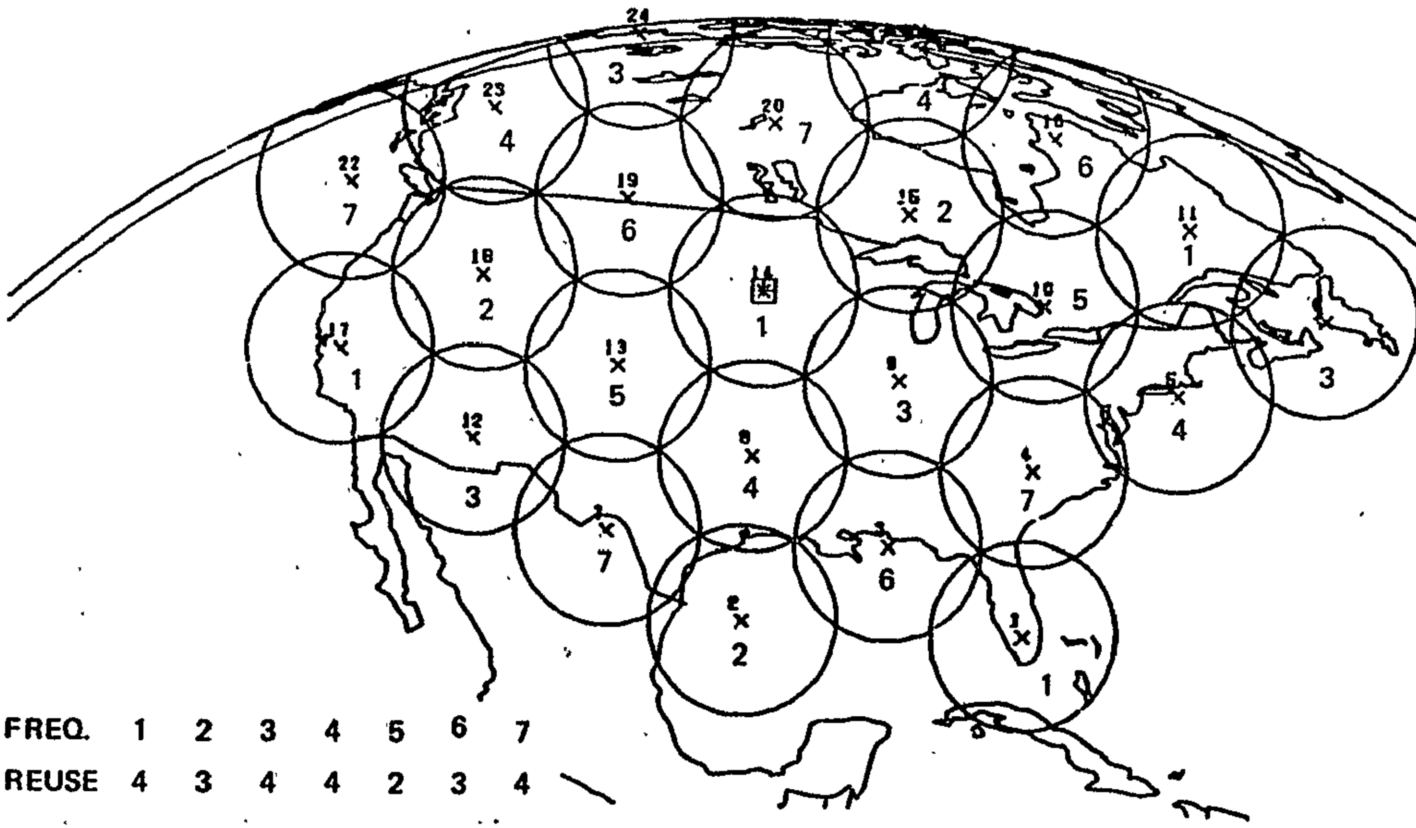
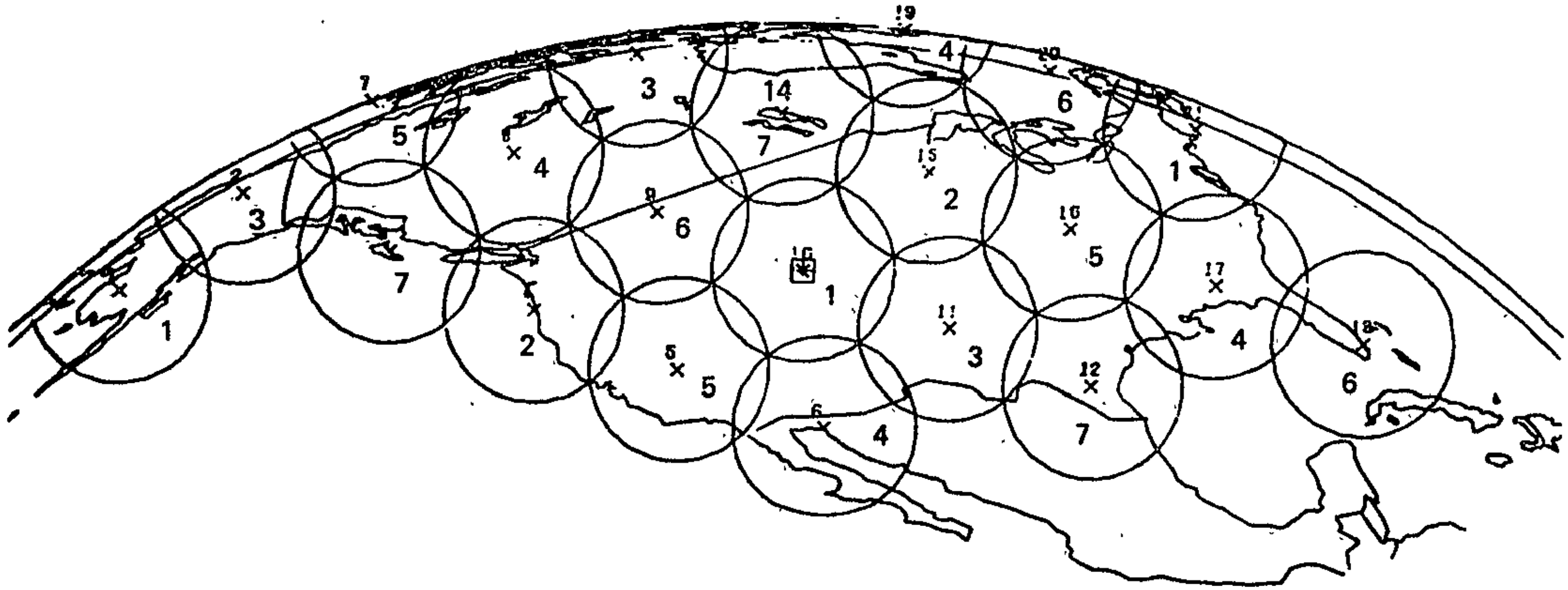


Figure 13. MSAT-2 Satellite Antenna Beam Layout, 7-Frequency Reuse
Antenna Diameter: 20m; f = 845.5-MHz Crossover Beamwidth: 1.4°;
Crossover Gain: 37.5 dB Satellite Position: 90°W Longitude Geostationary Orbit



FREQ.	1	2	3	4	5	6	7
REUSE	3	2	3	4	3	3	3

Figure 14. MSAT-2 Satellite Antenna Beam Layout, 7-Frequency Reuse
Antenna Diameter: 20m; f = 845.5-MHz Crossover Beamwidth: 1.4°;
Crossover Gain: 37.5 dB Satellite Position: 130°W Longitude Geostationary Orbit

antenna much smaller than 10 m would result in a smaller capacity, and a system having an antenna much larger than 15 m would exceed the payload weight limit of the bus. Since the assumed L-band frequency is approximately twice the UHF frequency, the 10-m antenna is selected for the L-band system. Because the L-band antenna is a frequency-scaled version of the UHF antenna, the antenna gain, number of beams, interbeam isolation, and frequency reuse plan are approximately the same for both the UHF and L-band systems.

In the UHF design, the assumed mobile antenna is a mechanical MGA having an approximate gain of 10 dB. Instead of fixing the mobile antenna gain, three values (i.e., 10, 13, and 16 dB) are examined for the L-band system and the corresponding system capacity is estimated. Based on the estimated capacities, one mobile antenna is selected for the L-band system.

Following the same procedures as in the UHF design, the capacity of the L-band system, which consists of two satellites, has been estimated to be 3,800, 7,600, and 14,800 channels for the 10-, 13-, and 16-dB antennas, respectively. The capacity of the 13-dB case is twice that of the 10-dB case. The capacity of the 16-dB antenna is frequency limited and, therefore, is less than twice that of the 13-dB antenna.

Depending on the mobile antenna configuration, the capacity of the L-band system varies over a wide range. The 10-dB antenna is the simplest and smallest of the three antennas considered and its corresponding capacity is also the smallest. The 16-dB antenna offers the greatest capacity; however, this antenna may not be practical due to its size and cost. On the other hand, a 13-dB mechanical antenna, which yields a capacity comparable to that of the

UHF system, is very similar to the UHF mobile antenna in terms of its size and cost and, therefore, is considered more suitable for mobile applications.

Although the capacity of the L-band system using a 13-dB antenna is slightly less than that of the UHF system (7,600 channels versus 8,688 channels), because of the smaller antenna, the L-band satellite would have a smaller dimension in both the deployed and stowed positions, hence, lowering the launch cost and reducing the constraints on the attitude control subsystem on board the spacecraft. The net effect is a simpler spacecraft and the estimated monthly user cost is about the same as the UHF system.

4.0 USER COST ESTIMATES AND SENSITIVITY ANALYSIS

MSAT-2 is a commercial system. As such, it must be economically viable. To assess the financial health of the system, a user cost model has been developed using an electronic spreadsheet program. (A detailed description of this program is presented in Appendix C.) The estimated user costs for the UHF and the L-band systems previously mentioned are generated by this model. Additionally, this program has been used to analyze the impact of the available frequency bandwidth and mobile antennas on the user cost.

4.1 A 4-MHZ BAND VERSUS A 10-MHZ BAND

The MSAT-2 design assumes that a pair of bands of 10-MHz each will be available. The effects of only a 4-MHz availability are a concern. With a 4-MHz bandwidth, MSAT-2 would become frequency-limited to about 6,000 channels, compared to 8,688 channels for a 10-MHz band. The reduced capacity would

increase the charge rate from an estimated $0.20 to $0.25 per call-minute, or an increase of 25%. The loss of 6 MHz of bandwidth would cost the user a total of $40M annually, or $7M annually for each MHz of bandwidth lost.

4.2 TRADE-OFF BETWEEN MGA AND LGA

The cost model has also been used to analyze the impact of using an LGA instead of an MGA. The baseline design utilizes a mechanical MGA to alleviate the burden on the satellite. The electronically phased array is not considered because its estimated cost is substantially higher than the mechanical MGA. A few problems are associated with the mechanical MGA. The first is the size of the antenna. The estimated size of a mechanical antenna is 7.7 to 18 cm (3 to 7 inches) in height and 92 cm (36 inches) in diameter. Although this size is not prohibitive and it may be possible to reduce the size through further research and development, the LGA is much more compact. Physical size is not the only problem with the mechanical MGA. A mechanical MGA also requires a tracking system in the azimuthal direction due to its relatively narrow azimuthal beamwidth. Because of the dynamics of the environment in which the mobile vehicles operate, including the presence of multipath fading and the motions of the mobile vehicle, the requirement on the tracking system is very stringent and, therefore, complicates the design of the antenna. This is the second problem with the MGA that the LGA does not have. The third advantage an LGA has over an MGA is the cost. For the MGA assumed in the baseline design, which is a non-conformal mechanical antenna, the estimated cost is about $800 on a mass production basis. The estimated cost for an LGA is only $50.

Although the baseline design assumes an MGA, MSAT-2, with a 10-MHz bandwidth, can operate with all MGA terminals replaced by LGA terminals. The only effects are a capacity reduction by a factor of 4, and there would be no orbit reuse, due to the inability of the LGA to discriminate adjacent satellites. (It is noted that the assumed gain for the LGA is 4 dB.) The substantial difference in estimated antenna costs makes one wonder if the LGA would produce a lower user cost despite the reduction in satellite channels.

Estimated user cost indicates that the answer depends on the amount of usage and the actual cost of the antennas. Using the same satellite system, the estimated charge rate would be increased from $0.20 to $0.60 if all the MGA terminals were replaced by the LGA terminals. The terminal cost, in the form of a monthly installment, would be approximately $30 per month for the LGA based on an antenna cost of $50 per unit, and $45 for the MGA based on an antenna cost of $800 per unit. Therefore, for 37.5 call-minutes or less, the system using the LGA would result in a lower monthly cost. For a usage of 100 call-minutes per month, the estimated cost using LGA would be about $90 compared to $60 using the baseline MGA.

In addition to the dependence on the amount of usage, the trade-off between the MGA and LGA terminals is also contingent on the actual cost of the antennas. Although the estimated antenna costs represent the best available data, they are only estimates and there is some uncertainty. The range of uncertainty for the LGA is relatively narrow and thus will not have appreciable effects on the trade-off. The cost of the MGA, on the other hand, could vary over a much wider range and may have significant effects on the result of the trade-off. Figure 15 shows the threshold cost of the MGA as a function of the monthly

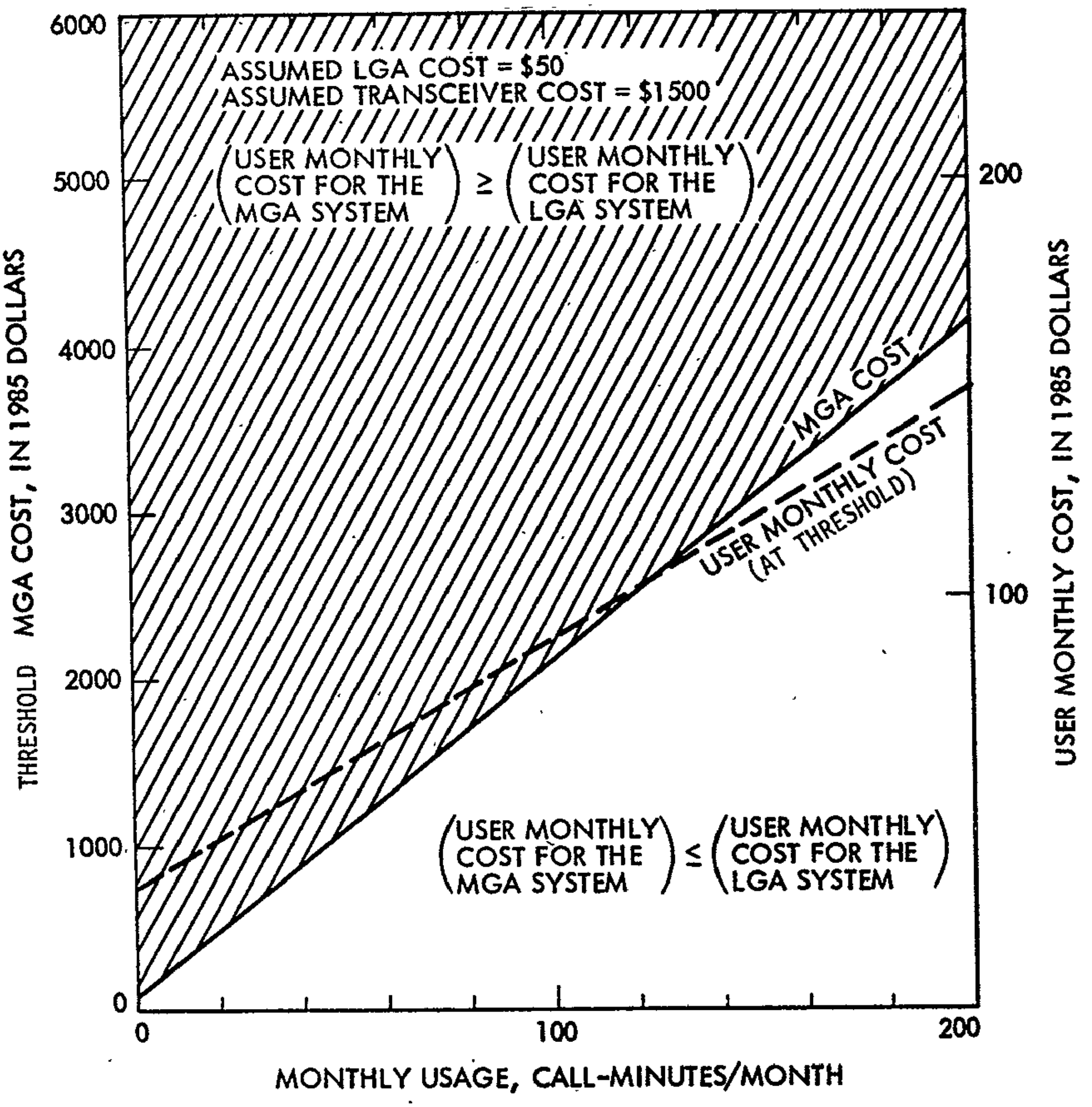


Figure 15. Threshold MGA Cost Versus Monthly Usage. (The Threshold MGA Cost is the Cost That Results in a User Monthly Cost Equal to that of a System Using an LGA Terminal.)

usage and summarizes the cost trade between the LGA and the MGA. The threshold MGA cost represents the upper limit beyond which the use of the MGA would no longer produce a user monthly cost that is lower than that of the LGA. For a usage of 100 call-minutes per month, the cost of the MGA can be as high as $2100 and still would have a lower monthly cost than the LGA. In other words, the cost-trade would still favor an MGA even if the actual cost is twice as much as the estimated cost. Implicit in the figure are the costs of the LGA and the mobile transceiver, which are assumed to be $50 and $1500, respectively. The threshold cost for the MGA is insensitive to the variation in the transceiver cost.

5.0 FURTHER STUDIES

The design of MSAT-2 is based on relatively simple satellite technologies. Complicated technologies such as BFN and on-board switching are not required. To ensure a timely implementation and to further improve the system, however, further studies are recommended in the following areas.

Although MSAT-2 offers a very large capacity, there is still room for further improvement, such as in the efficiency of the power amplifiers or in the design of the transponder to minimize the effects of the skewed user population that substantially reduces the effective capacity of MSAT-2. Another enhancement involves on-board signal processing, or on-board switching, which improves the link performance and enables the users to achieve mobile-to-mobile communications with a single hop. (The current design requires two hops.)

Due to limited resources, a detailed analysis of the structural characteristics of the antenna and its impact on attitude control has not been performed. Consequently, there is a degree of uncertainty associated with the adequacy of the attitude control subsystem. Further research to characterize the structural characteristics of the antenna and to assess the requirements on the control subsystem are recommended. The present antenna mast design concept is not optimal. The STS launch-charge factor, by the occupied length, is substantially higher than that by weight for the present design. To reduce the launch cost, other antenna mast designs with more efficient mechanical packaging should be explored.

The present design is based on a hypothetical 10-MHz allocation in the UHF band. Noting the possibility that only 4-MHz may become available in the UHF band, a future MSS may employ a hybrid UHF/L-band satellite in order to alleviate the UHF congestion. Such a hybrid system may be quite different from the UHF system in the payload design, antenna size, and the resulting capacity. An in-depth study is warranted.

The UHF system has also been designed for one type of mobile antenna. It is possible that future MSS's may, at times, operate in the presence of different types of mobile antennas. The compatibility of these antennas, the LGA and MGA in particular, must be examined.

International cooperation is essential to the success of future MSS's. Both the U.S. and Canada are seriously considering launching an MSS. It is prudent for the promoters on both sides of the border to secure an agreement to share the available frequency band and/or the satellite capacity. Investigations to determine an appropriate sharing scheme, which may dictate the number of satellites required by the system, are recommended in the immediate future in order to benefit the first-generation system.

PART TWO

DESIGN AND TRADE-OFF

CHAPTER 1

INTRODUCTION

1.0 INTRODUCTION

Recently, there has been a lot of interest in the Mobile Satellite System (MSS). The Federal Communications Commission (FCC) issued a Notice of Proposed Rulemaking (NPRM) in January 1985 for a frequency allocation for the Mobile Satellite System. Within a few short years, there will be a mobile satellite system, providing mobile services to hundreds of thousands of users across the United States and Canada. This report presents results of a study on a second-generation mobile satellite system. The primary objective of this study is to perform a conceptual design of a second-generation mobile satellite to be launched around the mid-1990's. The secondary objective is to examine various issues related to the mobile satellite system in general, and the second generation in particular.

The tradeoff studies are presented in Chapter 2. Results of the tradeoff studies lead to a baseline design of a second-generation mobile satellite, employing a large deployable antenna, operating at UHF, and capable of providing services to almost one million users. The detailed design of this satellite is presented in Chapter 3.

The key to support a large number of users is an efficient networking scheme. Chapter 4 discusses the networking concept for the second-generation mobile satellite system.

While the baseline system operates at UHF, an alternative system operating in the L-band is examined in Chapter 5. The relative advantages and disadvantages between a UHF system and an L-band system are also discussed.

Chapter 6 analyzes the sensitivity of the cost to the users of the mobile satellite system. The effects of the available frequency band, the design of the mobile antenna, and the channel spacing are addressed.

The areas of further research and development required to enable the implementation of a second-generation satellite system are identified in Chapter 7.

The rest of this chapter is to provide background information on the mobile satellite system concept, and to state the specific objectives and ground rules of the study.

1.1 BACKGROUND ON THE MOBILE SATELLITE SYSTEM CONCEPT

Communication plays a very important role in the advances of human civilization. In ancient times, communication was very limited due to physical barriers such as distance and terrain. Communicating over a long distance was slow, if possible at all. Due to advances in technology, physical barriers are no longer the major obstacles. The telephone system allows conversation over a long distance across mountains, oceans, and continents. The telephone's usefulness, however, is limited to exchange between fixed points.

Although fixed-point communication probably accounts for a major portion of today's communications, there exists a need for a special kind of system to provide mobility. The term "mobile communication" refers to communication which involves at least one mobile party. A study performed by the General Electric Company (GE) has indicated the existence of such needs [1]. Similar conclusions can also be drawn from other studies, including a survey performed by JPL [2].

The need and desire for a mobile system arises from many situations. It may be of financial importance in some cases, such as the need of an employer to contact his employee traveling in a vehicle hundreds of miles away. In other cases, the necessity may be more than just financial, such as in an emergency in the wilderness or a sparsely populated area where conventional telephones are not available. In these situations, whether one can summon help hundreds of miles away could mean the difference between life and death. Regardless of what the situation is, often it is necessary and desirable to be able to communicate when and where it is needed. This cannot be fulfilled by a conventional telephone system.

Although, the development of terrestrial mobile telephone systems, such as the cellular system, have satisfied many, it too has limitations. The existing cellular system operates mainly in major metropolitan areas. Even with a possible future expansion to cover major highways, there is still a lot of area not covered by the cellular system. A system that can provide mobile communication service to a wide geographical area, such as the entire contiguous

United States (CONUS) is thus needed. A mobile satellite system, which is a satellite-based communication network, would fulfill this need.

The concept of a mobile satellite system is a natural extension of, and is not much different from, the terrestrial mobile telephone systems, which are familiar to many. A typical terrestrial mobile telephone system consists of many mobile terminals, a number of repeaters, and one or more base stations. A typical terrestrial mobile telephone system operates as follows:

To place a call from a mobile vehicle to a fixed receiver, such as the telephone in one's office or residence, the call is first generated and transmitted by the mobile terminal and subsequently picked up by a nearby repeater, which in turn retransmits the call to a base station via a radio frequency (RF) link at a different frequency. The base station completes the rest of the communication path by connecting the call to its destiny via a regular telephone network. To call a mobile user from a fixed telephone, the procedure is reversed.

The interface between the terrestrial mobile phone system and the regular telephone network allows the mobile users to have access to and be accessed by any telephone in the country. To avoid interference, the transmitted frequencies of the mobile terminal, the repeater, and the gateway are generally different from each other and are remotely separated from the received frequencies. In a duplex operation which involves signals to be transmitted

and received in both directions, a pair of frequency channels are needed for each RF link. Because of the limited spectrum allocated for mobile service, efficient utilization is a must. The cellular system achieves this goal through the use of a cell topology. In this system, the service area is divided into a number of small regions called "cells." Similarly, the allocated spectrum is also divided into a number of small bands called "frequency subbands." Each cell is assigned to operate in one of these frequency subbands, with some or all of these subbands being assigned to more than one cell. To avoid interference, the assignment is such that adjacent cells do not operate in the same subband. Through this scheme, the cellular system achieves frequency reuse and accommodates a large number of users.

A mobile satellite system is very similar to the terrestrial system, with its geostationary satellite serving the function of the repeaters in a terrestrial system. To achieve frequency reuse, a mobile satellite system employs multiple spot beams to cover the service area. The footprints of the beams are analogous to the cells in the cellular system. A brief description of a mobile satellite is given in Section 1.2.

1.2 DESCRIPTION OF THE MOBILE SATELLITE NETWORK

There has been a lot of interest in the mobile satellite system in recent years in both Canada and the United States. Many conceptual studies have been performed by the government and the private sector [1, 3, and 7]. Some of these studies [4, 5, and 7] are generally based on current technology and are geared toward immediate operation. Some other studies, such as the 55-meter system studied by JPL [3], requires improvements over the current state-of-the-art

technology and is aimed at operating in the year 2000 and beyond. Despite the difference in the system capacity, complexity and operation time frame, the network operation and its basic ingredients are essentially the same and they all are capable of providing voice and data services to a vast geographic area such as the entire CONUS.

A mobile satellite network, as conceived today, consists of these elements: mobile terminals, one or more satellites at the geostationary orbit, gateway stations, base stations, and one or more Network Management Centers (NMC). A typical mobile satellite network is shown in Figure 1-1. Two types of base stations are depicted in the figure: one operating at the backhaul frequency and one at the service link frequency. The communication modes, types of service, service area, and the elements of a mobile satellite system are discussed in general terms in the following paragraphs. Specific detailed discussions applicable to the first, second, and third generation mobile satellite systems are provided in Section 1.3.

1.2.1 Modes of Communications

Similar to the terrestrial system, a mobile satellite system as conceived would provide three types of communications: mobile to mobile, mobile to fixed station, and fixed station to mobile. Different types of communications are provided using a combination of the service links and the backhaul links. (The term "service links" refers to the RF links between the mobile terminal and the satellite, and "backhaul links" are those between the satellite and the gateway station, NMC, and some base stations.) Although

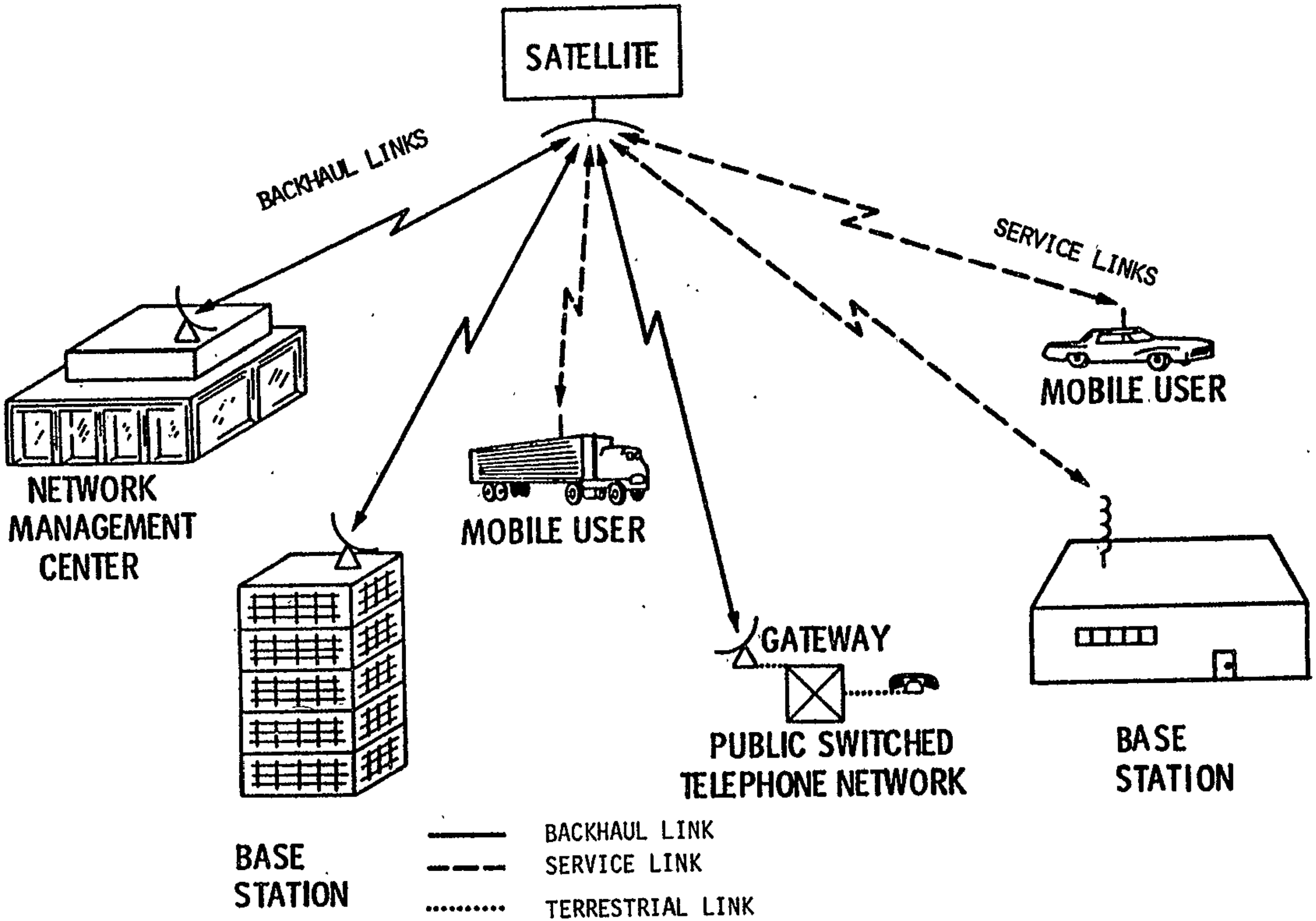


Figure 1-1. A Mobile Satellite Network

there is no formal frequency allocation for mobile satellite services to date, it is generally assumed that the service link frequency will be different from the backhaul frequency. More discussion about the possible operating frequencies is provided in Section 1.5.

The fixed-station-to-mobile and the mobile-to-fixed-station communications involve a mobile user, the satellite, the gateway station, and a fixed station, which may be part of another communication network. The mobile-to-fixed-station communications start when the mobile user transmits his or her message using the service link. The transmitted signal is received and transponded to the gateway station by the satellite via the backhaul link. The gateway, upon reception of the signal, connects the signal to its destiny via another network such as a conventional telephone network. A mobile-to-fixed-station communication is thus established. The fixed-station-to-mobile communication works exactly the same way but in the reversed order. The fixed-station-to-mobile and the mobile-to-fixed-station communications together offer a duplex communication between a mobile user and a fixed station. Figure 1-2 depicts these communication links. As indicated in the figure, only one hop is required to route the message from one end of the link to the other.

Unlike the fixed-station-to-mobile and the mobile-to-fixed-station communications, mobile-to-mobile communication requires two hops and it involves two mobile users, the satellite, and the gateway. The first hop brings the signal from one mobile user to the gateway and the second hop brings the signal from the gateway to the other user. The gateway serves as a midpoint for this mode of operation (Figure 1-3).

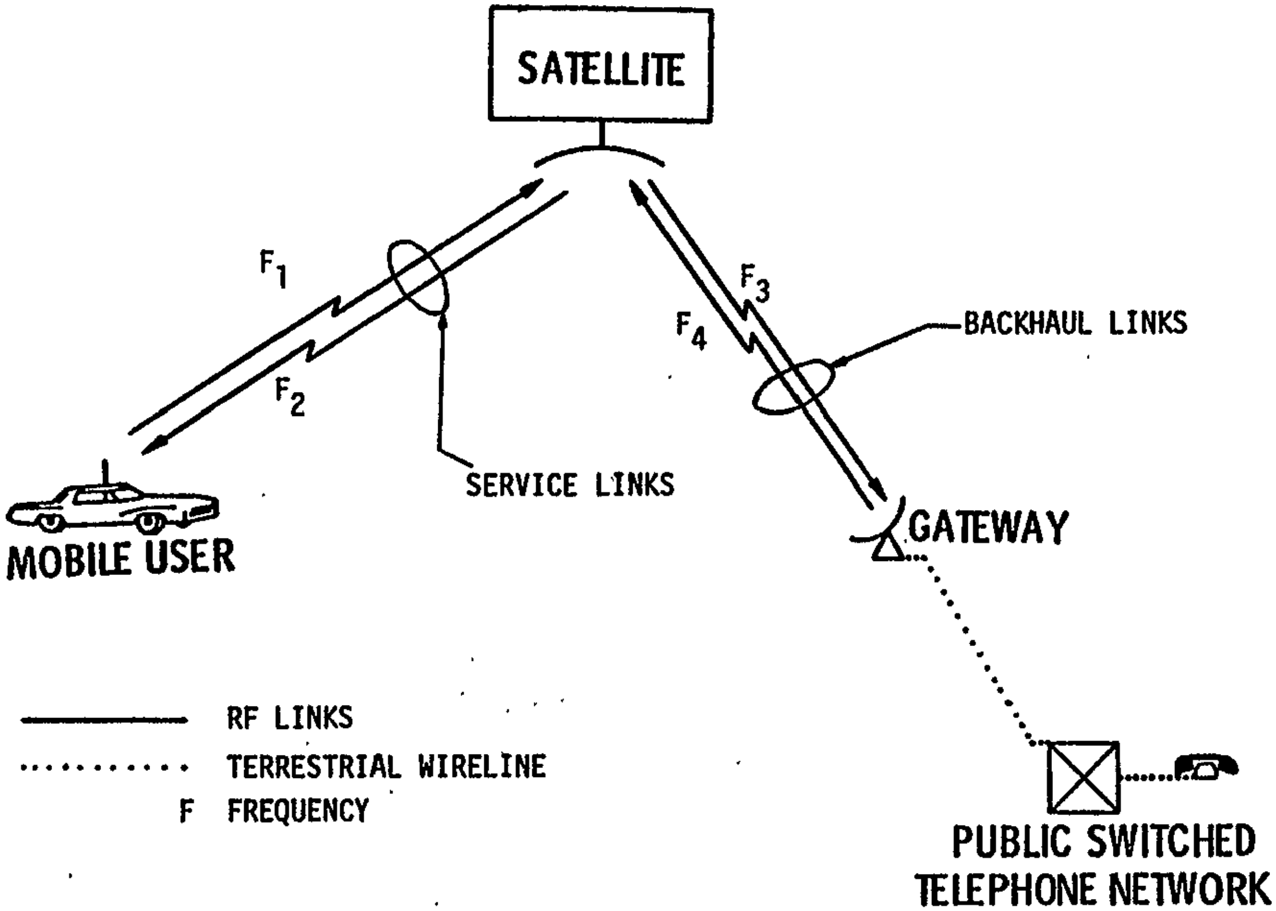


Figure 1-2. Fixed-Station-to-Mobile and Mobile-to-Fixed-Station Communications

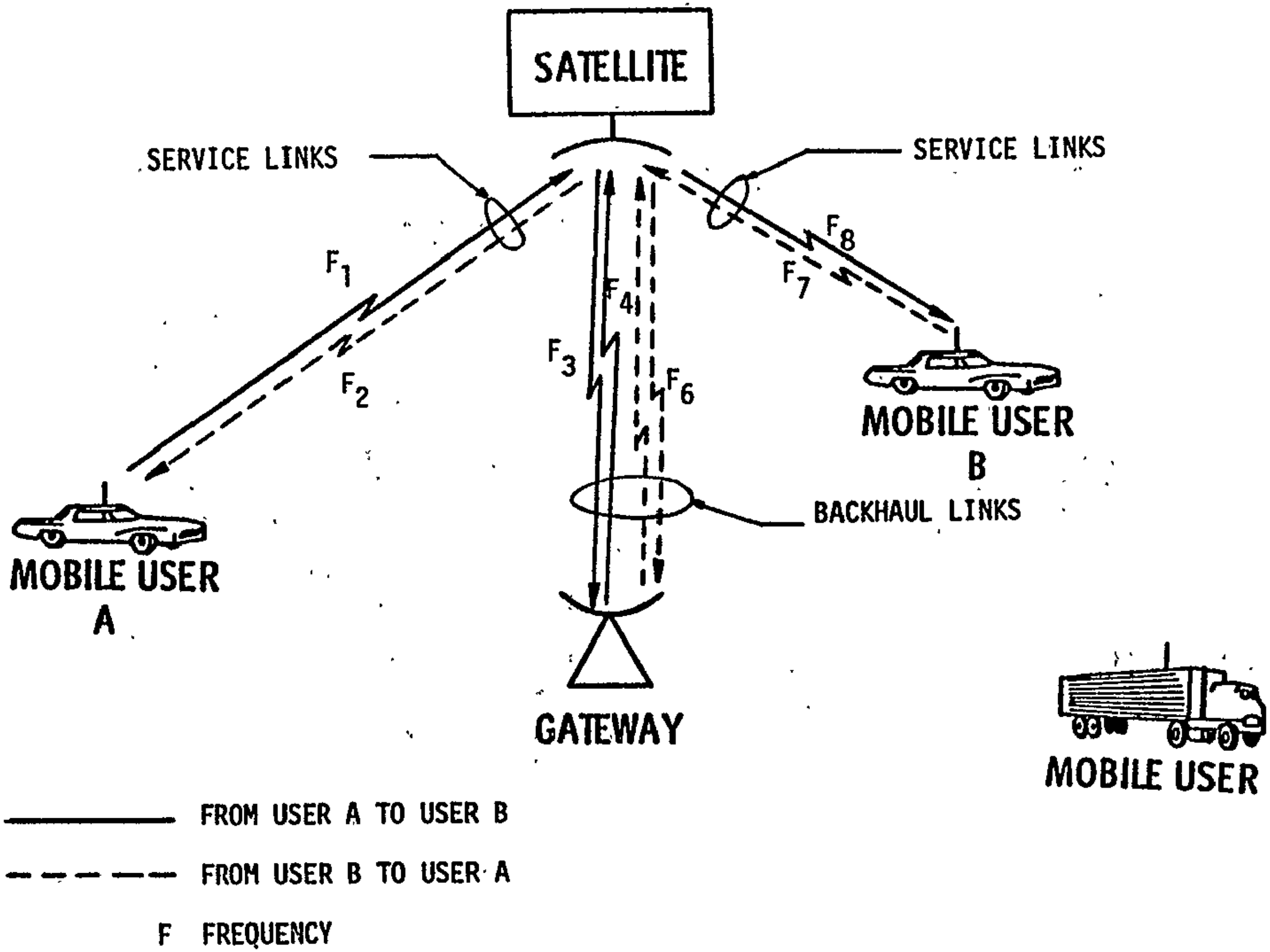


Figure 1-3. Mobile-to-Mobile Communications

1.2.2 Types of Services

A mobile satellite system can provide many types of services. Its usage is limited only to one's imagination. Some often-mentioned services include the following [8]:

- o Mobile telephone
- o Radio dispatch
- o Rural telephone
- o Aeronautical service
- o Position location and surveillance
- o Electronic messaging or mail to and from mobile units, and
- o Emergency communication for disaster relief.

Many of these services can be in the form of analog voice or a digital data stream. Although a mobile satellite system can provide both analog voice and digital data channels, and voice communications probably constitute a major portion of today's communications, analog voice is not an efficient way of transferring information because of its low information rate. It is expected that more services will be provided using digital data streams, including the mobile telephone service.

1.2.3 Service Area

Various mobile satellite systems studied in [1, 3, 4, 5, 6, and 7] are all capable of providing services to a vast geographical area, such as the entire CONUS. The large service area is a characteristic of a mobile satellite system which is difficult to achieve for a terrestrial system. A large area

encompasses a larger number of users. Because of the economics of scale, this lowers the cost per user and makes the mobile satellite system financially sound.

1.2.4 Network Access Scheme

Various schemes have been employed by communication systems to provide multiple access to users. Some often used schemes are Time Division Multiple Access (TDMA), Code Division Multiple Access (CDMA), and Frequency Division Multiple Access (FDMA). Each scheme has its advantages and disadvantages and its applicability to a particular system depends on the operating environment of that system. The mobile satellite systems in [3, 4, and 5] employ Frequency Division Multiplexing (FDM) with a single channel per carrier (SCPC) and a demand assignment multiple access (DAMA) scheme, or SCPC-FDM-DAMA.

1.2.5 Elements of a Mobile Satellite System

A mobile satellite system consists of, as previously mentioned, mobile terminals, gateway stations, base stations, NMC's, and, of course, one or more geostationary satellites. The term "mobile satellite system" is synonymous to "mobile satellite network" in this report and the term "satellite system" refers only to the space segment. Although the characteristics of the elements of the mobile satellite system may vary slightly from one system to another, their primary functions are essentially the same. A brief description of the general characteristics of these elements and their functions in the network are provided in the following paragraphs, with the understanding of possible deviations from systems studied in [1, 3, 4, 5, 6, and 7].

The mobile terminals are the vehicle-mounted or portable equipment. Their function is to enable the mobile user to transmit and receive signals to and from the satellite via the service links. The basic components of a mobile terminal include the transceiver, antenna, and user interface. The actual implementation of a mobile terminal depends on the type of service it provides. For example, a mobile telephone terminal will have a telephone handset and a touch-tone pad in addition to the basic transceiver and antenna. If digital voice is employed, a vocoder will also be required. If the terminal is used for alphanumeric digital service, an alphanumeric digital display will be needed.

The function of the satellite in a mobile satellite system is similar to the repeaters in a terrestrial mobile telephone system. By using the service and the backhaul radio links, the satellites connect the mobile terminals to the gateways and base stations, and vice versa. The service links, as mentioned before, are the links between the satellites and the mobile terminals, and the backhaul links are between the satellites and the gateways or base stations. The design of the satellite is the heart of the study and will be addressed in detail in Chapters 2, 3, and 4.

The purpose of the gateway stations is to provide an interface between the mobile satellite network and other networks such as the Public Switched Telephone Network (PSTN). This allows the user in the mobile satellite system to be able to communicate with users of other networks such as the telephone network. In addition, the gateway also serves as a mid-point in the mobile-to-mobile communication.

A base station is similar to a gateway station with the exception that it may not necessarily be connected to the PSTN or other networks. The base stations are normally used for dispatch operation and, hence, require less channels and less capabilities than the gateway stations. A base station may be privately owned, whereas the gateway stations will probably be owned by the system operators. For example, the base station may be owned by a cross-country trucking company and used as a dispatch center. Using this base station, a company dispatcher can, through the satellite, communicate with his or her fleet of trucks anywhere in the covered area. Two types of base stations have been mentioned in the existing literature: one operates at the service link frequency and the other operates at the backhaul frequency. More on the base station operating frequency will be given later.

The NMC is the heart of the mobile satellite network and has the responsibility of controlling the operations of the network. Its primary functions are to assign frequency channels, monitor the network traffic, plan the best call routes, and collect billing information. Depending on the system design, there may be more than one NMC. Under this situation, the NMC's are also responsible for coordinating their activities with each other.

1.3 CLASSIFICATIONS OF MOBILE SATELLITE SYSTEMS AND THEIR CHARACTERISTICS

A brief description of a mobile satellite system in general terms has been provided in Section 1.2. A more specific description and classification of mobile satellite systems are being addressed in this section. Recent interest in mobile satellite systems has resulted in many conceptual studies and a few proposed systems. The capacity and complexity of these systems vary over a wide range. For example, the size of the satellite antenna considered ranges from a few meters to 55 m, and the number of spot beams varies from a few to about 100. For the purpose of this study, mobile satellite systems are conveniently classified into three categories according to their system capacity, technology, and operation time frame. Specifically, the three classifications are the first, second, and third generation systems.

Interests in a commercial mobile satellite system have spurred several companies to file applications to the FCC for a license to build and launch such a system. Most of the proposed systems are essentially based on current satellite technology and are designed to operate in the immediate future, roughly from 1986 to 1995. This type of system is classified as the first generation.

On the other hand, the system studied by JPL [3] which utilizes a 55-m antenna is very complex and requires technology improvement. This type of system is classified as the third generation and is not expected to be implemented prior to the year 2000. The gap between the first and the third generation systems is filled by the second generation which falls in the time frame of the mid-1990's to the early 2000's and is the subject of this study.

1.3.1 First-Generation System

The systems such as those proposed by current applicants are considered as the first-generation mobile satellite systems. Such a system consists of two satellites employing antennas of about 5 to 8 meters, provides services to CONUS, Canada, and Alaska, and has less than 10 multiple beams. The satellite bus may be a PAM-D class, off-the-shelf communications satellite bus, which is capable of generating about 1 kW of spacecraft power and weighs about 1500 lbs at the beginning of life (BOL). The satellite probably can support a few hundred channels. Because of the system's small antennas and limited spacecraft power, extensive frequency reuse is not anticipated. Some possible features of a first-generation system are tabulated in Table 1-1. The beam contours of a typical first-generation system are shown in Figures 1-4 to 1-6 for a 2-, 3-, and 4-beam system with antenna size ranging from 5 to 8 meters [8].

Table 1-1.

Possible Features of the First-Generation

Mobile Satellite System

No. of Satellites	2
Antenna Size, m	5-8
No. of Beams Per Satellite	10 or less
Spacecraft Weight @ BOL, lbs	1500
Launch Vehicle	STS-PAM-D Class
Coverage	CONUS, Alaska and Canada
Spectrum Requirement	
Service Link Freq. Band	UHF
Service Link Freq. Bandwidth, MHz	4
Backhaul Freq. Band	Ku
Backhaul Freq. Bandwidth, MHz	4
User Access Scheme	SCPC-FDM-DAMA

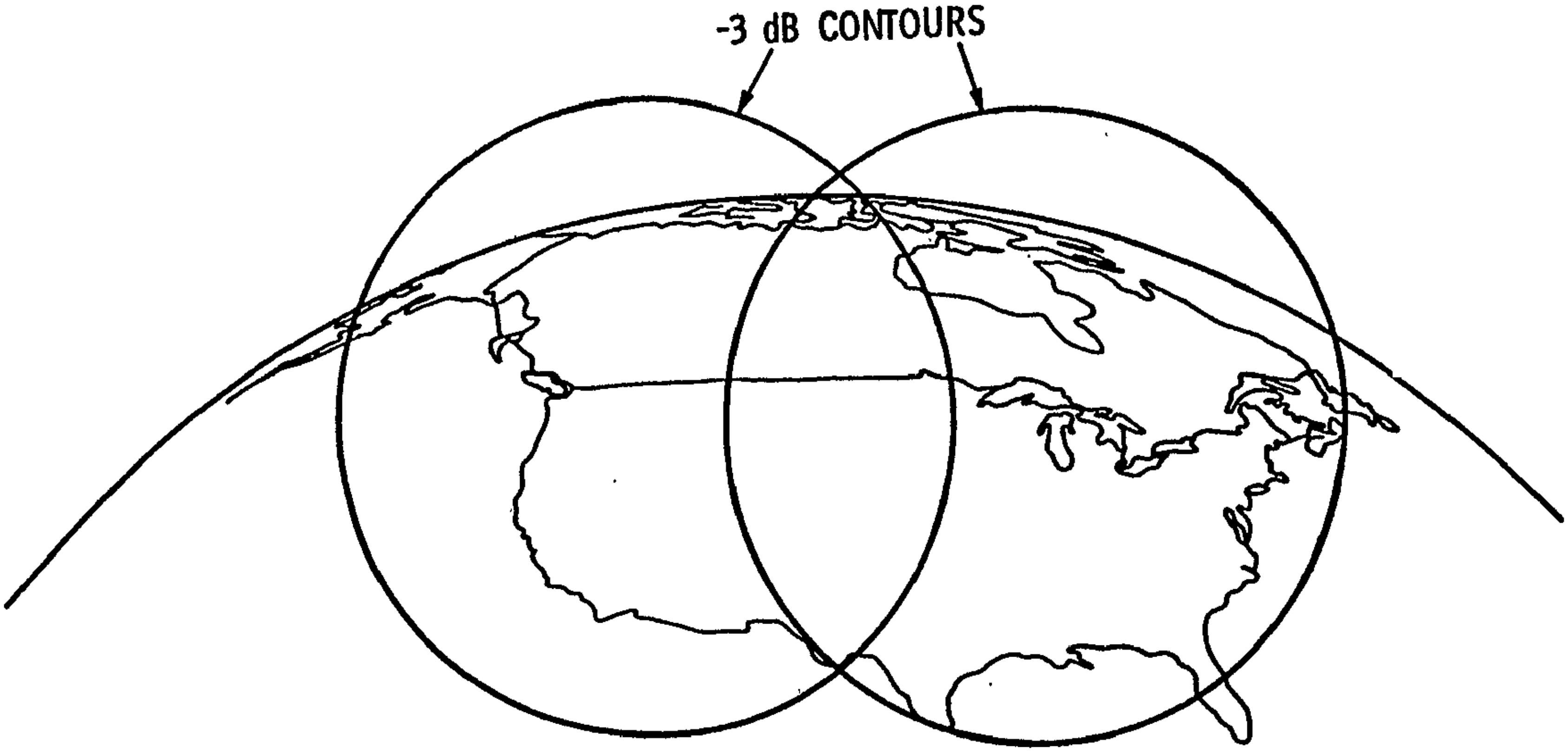


Figure 1-4. The UHF Beam Contours Produced by a 16-foot (4.9-m) Spacecraft Antenna

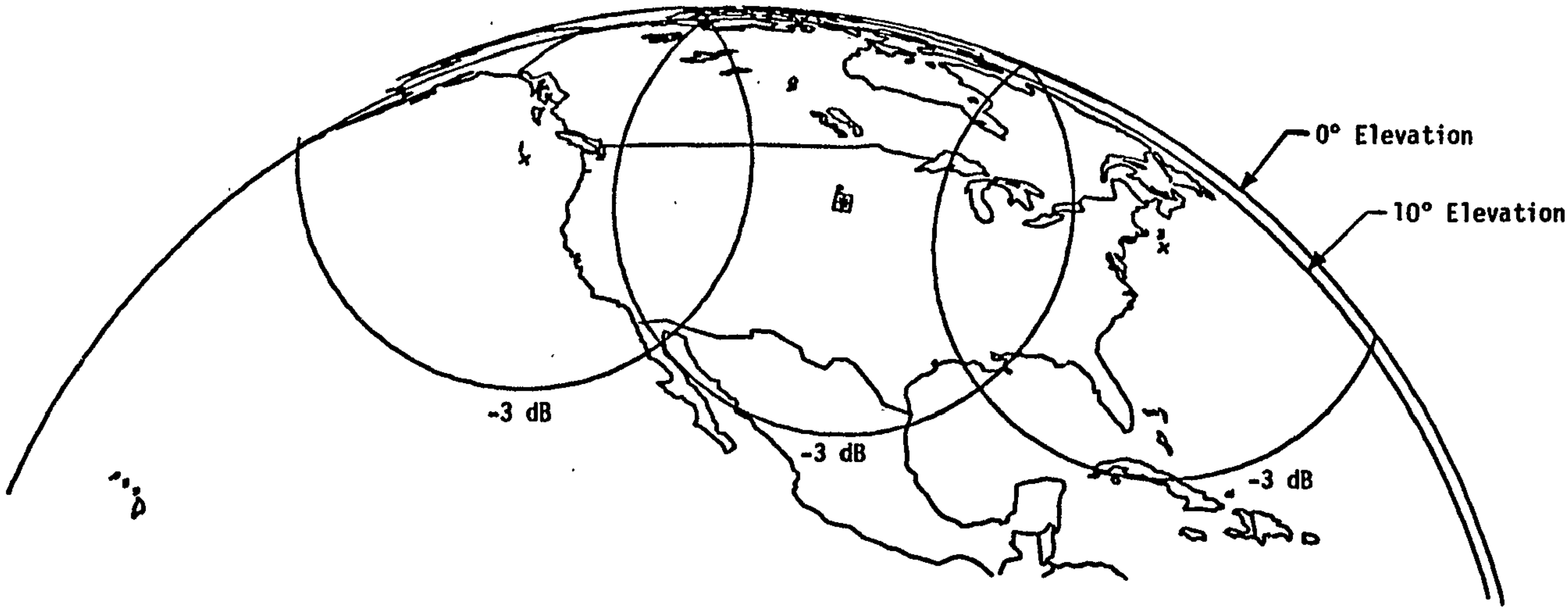


Figure 1-5. The UHF Beam Contours Produced by a 17.5-Foot (5.3-M) Spacecraft Antenna

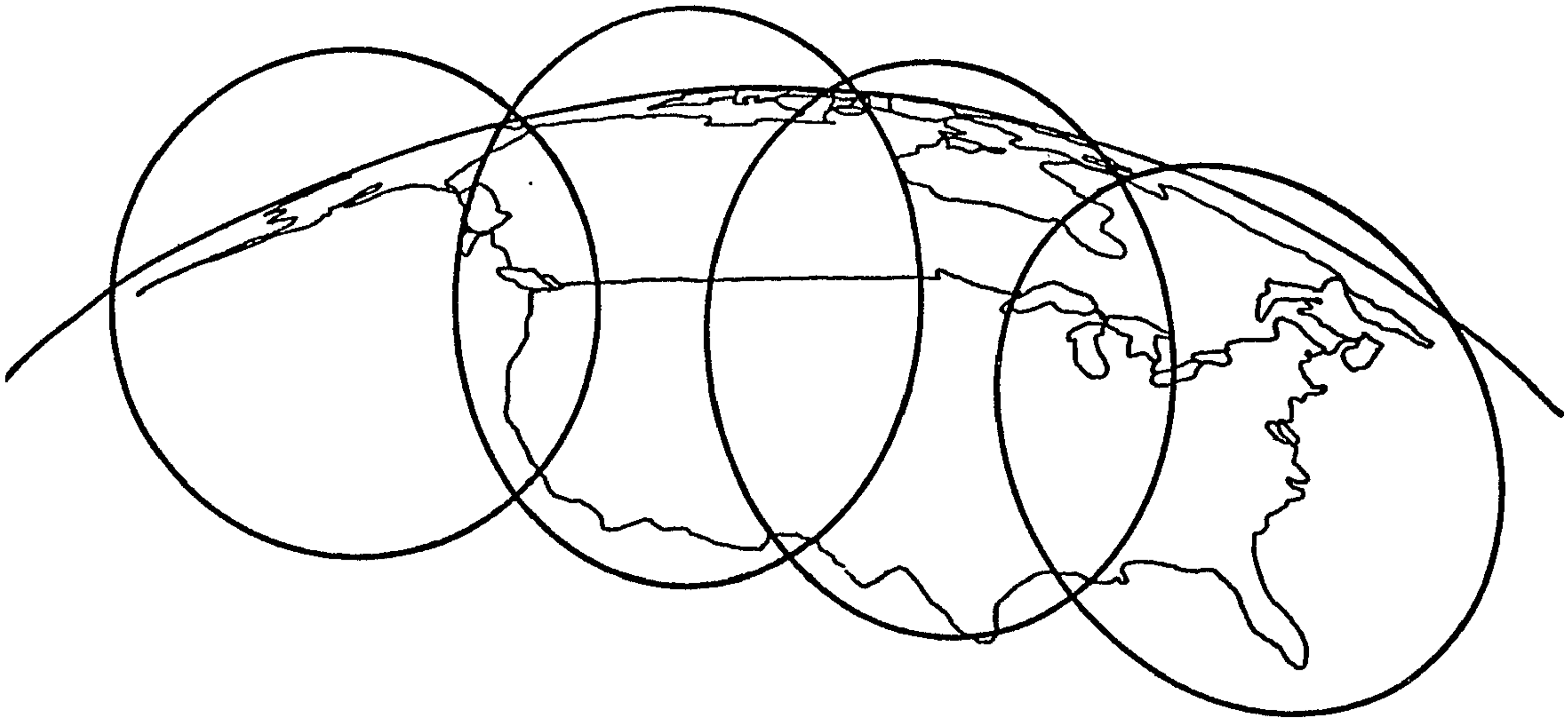


Figure 1-6. The UHF Beam Contours Produced by a Tailored Illumination of 25-foot (7.6-m) Spacecraft Antenna(s)

1.3.2 Third-Generation System

Unlike the systems first generation, the 55-m system studied by JPL [3] requires a much more advanced satellite technology. This system is characterized by its huge space structure, complex satellite designs, enormous spacecraft power, and very heavy customized spacecraft. It is used as a representative of the third-generation systems operating in the year 2000 and beyond. Because of the large antenna and its supporting structure, a special attitude control subsystem that is much different from those on current commercial satellites is needed. The satellite weighs about 9000 lbs at BOL and occupies a full STS cargo bay at launch. It generates 10 kW of spacecraft power at BOL and radiates about 1 kW of RF power -- enough to power up thousands of channels. It is designed to operate in the UHF for the service links and in the S-band for the backhaul links. It has 87 UHF beams and 25 S-band beams, and can provide services to the entire CONUS. The system is designed to operate in a 20-MHz allocation in the UHF band with 10 MHz for uplink and 10 MHz for downlink, and 70 MHz in the S-band.

Frequency reuse is necessary in both the UHF and S-band. The UHF spectrum is reused as many as 12 times on the average. The high reuse factor would result in a severe cochannel interference. To abate cochannel interference, a stringent requirement on the sidelobe level of 27 dB is imposed on the UHF antenna. This dictates the use of an overlapping antenna feed which is very complex and heavy and represents one of the technological challenges posed by the system. The salient features of the 55-m system are shown in Table 1-2. A conceptual drawing of the 55-m satellite is shown in Figure 1-7, and a polar perspective map showing the footprints of the 87 beams is given in Figure 1-8. Both Figure 1-7 and Figure 1-8 are obtained from [3].

Table 1-2.

Salient Features of the 55-m System

Location	110° W Longitude (Geostationary Orbit)
Coverage Area	CONUS
Frequencies	
- Mobile Vehicle - Satellite	UHF
- Base Station - Satellite	S-Band
Number of Voice Channels	8,265
EIRP-Per-Channel (UHF)	46.8 dBW
Number of UHF Beams	87
Number of S-band Beams	25
Beginning-of-Life DC Power	10 kW
Lifetime	10 years
Launch	Single Shuttle
Weight @ BOL	4,000 kg

ORIGINAL PAGE IS
OF POOR QUALITY

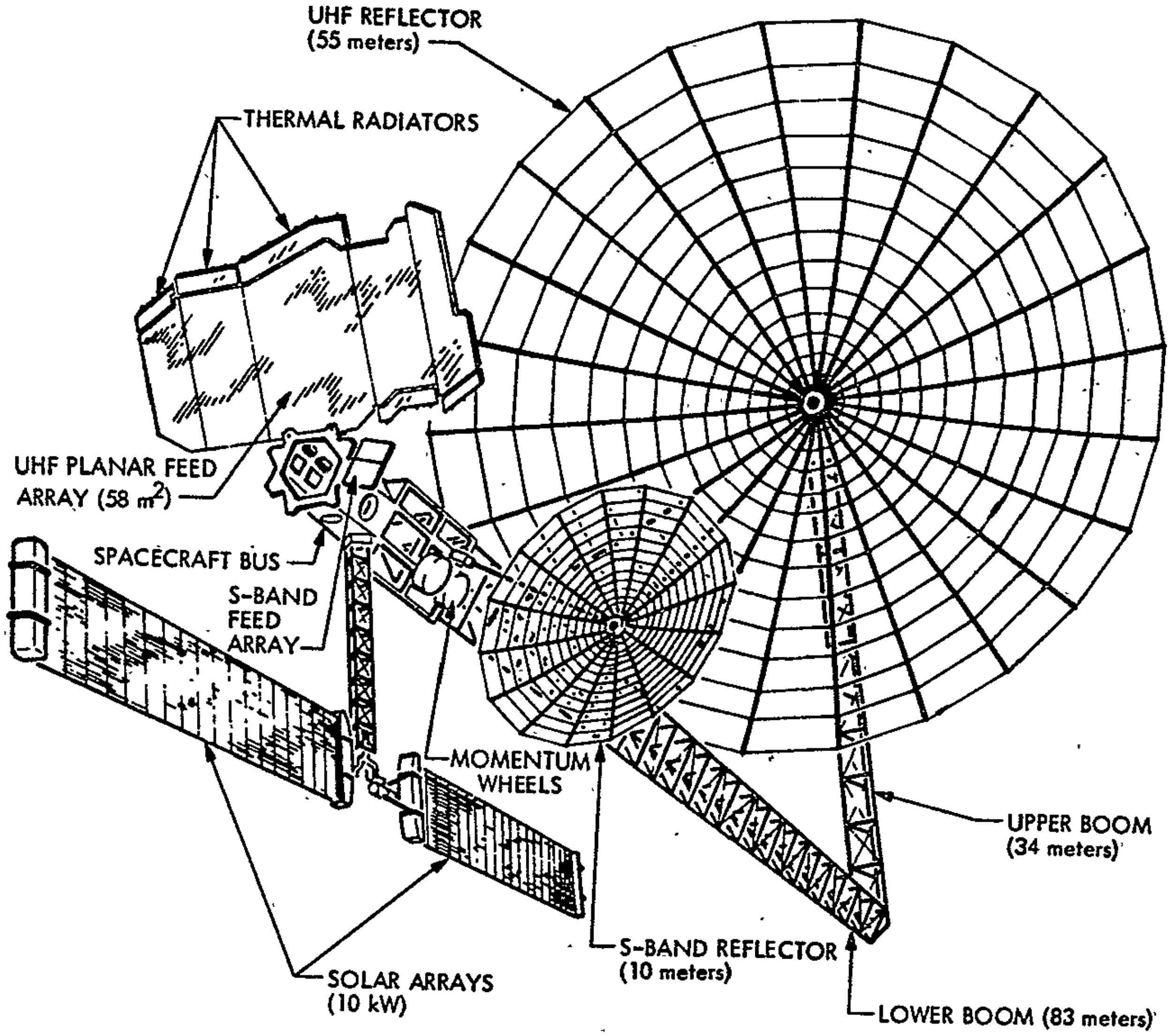


Figure 1-7. A Conceptual Drawing of the 55-m Satellite

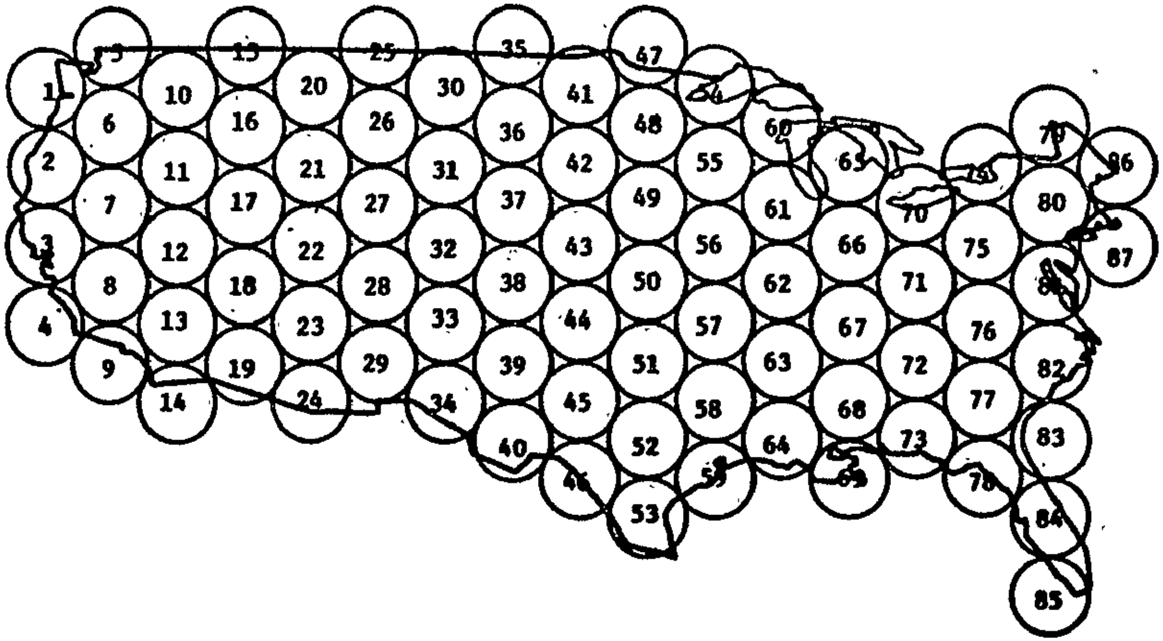


Figure 1-8. The UHF Beam Layout of the 55-m System (A Polar Perspective Map)

1.3.3 Second-Generation System

The transition from a system employing a 5- to 10-meter antenna to a system using a 55-meter antenna represents a huge jump in both antenna technology and satellite technology. A smooth transition would require the introduction of a satellite system that utilizes a 20- to 30-meter antenna, and is somewhere in between the first-generation and the third-generation systems in terms of satellite size, power, and capacity. This is the so-called second-generation mobile satellite system, or MSAT-2 for short, which is the subject of this study. The second-generation system is expected to have 20 to 30 beams and a moderate capacity. It would have some of the features of the first-generation system, such as utilizing commercial satellite buses, and some of the features of the third-generation system, such as frequency reuse. More detailed descriptions and designs of the second-generation mobile satellite system are provided in Chapters 2, 3, 4, and 5. The objectives and or requirements of the study are discussed in the following section.

1.4 STUDY OBJECTIVES

The primary objectives of the study are: to perform a conceptual design of a second-generation mobile satellite operating at the UHF frequency in the time frame of the years 1990 to 2000; to perform various parametric tradeoffs to produce a cost-effective design; and to aid MSAT-X and other NASA MSS technology programs setting development priorities. (MSAT-X is a NASA-funded program. Its primary objectives are to develop advanced ground segment technologies and techniques for use in the future mobile satellite systems, and to experimentally verify these technologies using the first-generation commercial mobile satellite system.)

Secondary objectives are:

- To identify technology development required for the second-generation mobile satellites,
- To perform an alternative satellite design using L-band instead of UHF, and
- To analyze various issues associated with a mobile satellite system in general and the second generation in particular.

The issues to be addressed include the following:

- The impact of frequency allocations, i.e., 10 MHz versus 4 MHz, and
- The type of mobile antenna, i.e., medium-gain antenna (MGA) versus low-gain antenna (LGA).

1.5 GROUND RULES

The design of a mobile satellite system involves many tradeoffs. To limit the scope of the study, a number of assumptions will be used, ranging from the system level down to the subsystem level. In order to efficiently utilize the available resources, many assumptions will be based upon the work performed under the MSAT-X program. Particularly, assumptions on the mobile terminal, network operations, and modulation schemes will be derived from MSAT-X.

Some of the system-level assumptions are actually requirements -- an example is the service area and the operation time frame. Requirements will be given in the following paragraphs without justifications. Some assumptions may be the result of a simple trade-off. In this case, they will be described and their justifications will be given. For those that are based on MSAT-X work, they may be given with or without justifications.

1.5.1. Service Area

The second-generation mobile satellite system is required to provide reliable services to CONUS, Alaska, and Canada. Because of the vast geographical area, the Earth-station-to-satellite elevation angle will vary over a wide range. To maintain an acceptable performance, a different requirement may be imposed on the mobile terminal operating in areas with a low elevation angle, such as Canada and Alaska. Because it is very difficult to provide reliable services at extremely low elevation angles, it is understood as part of the coverage requirement that parts of Alaska and Canada will not be covered. In addition, it should be noted that the mobile satellite is to complement, not compete against, the terrestrial mobile phone system. It therefore is not required to provide services to the urban area where services can be obtained from existing cellular systems.

1.5.2 Operation Time Frame and Technology

The second generation is to be launched around the mid-1990's. Consequently the satellite should be designed using 1990 technology. This allows some improvement in a number of areas over the current technology upon which the first-generation systems are based. The areas of possible improvement include transponder efficiency, satellite power, and weight capability.

1.5.3 Operating Frequencies, Bandwidth, and Channel Spacing

The links between the satellite and the mobile terminals are classified as the Mobile Satellite Service according to CCIR (International Radio Consultative Committee) regulations, and the backhaul links i.e., the links between the satellite and the gateway stations, are the Fixed Satellite Service. Various mobile satellite systems in [1, 3, 4, 5, 6, and 7] have assumed either UHF or L-band for the service links and Ku-or S-band for the backhaul links. To date, there is no formal frequency allocation in the U. S. for the Mobile Satellite Service in either the UHF or L-band. (It is noted that the Radio Regulations contains an allocation for mobile satellite service for Region 2 in the 806 to 890 MHz band.) The choice of the UHF band originally was to take advantage of the technology of the cellular system which operates in the UHF band. For the second-generation system, both the UHF and the L-band frequencies will be treated as a possible operating frequency for the service links. The UHF frequency will be used in the baseline system, and the L-band frequency in the alternative system.

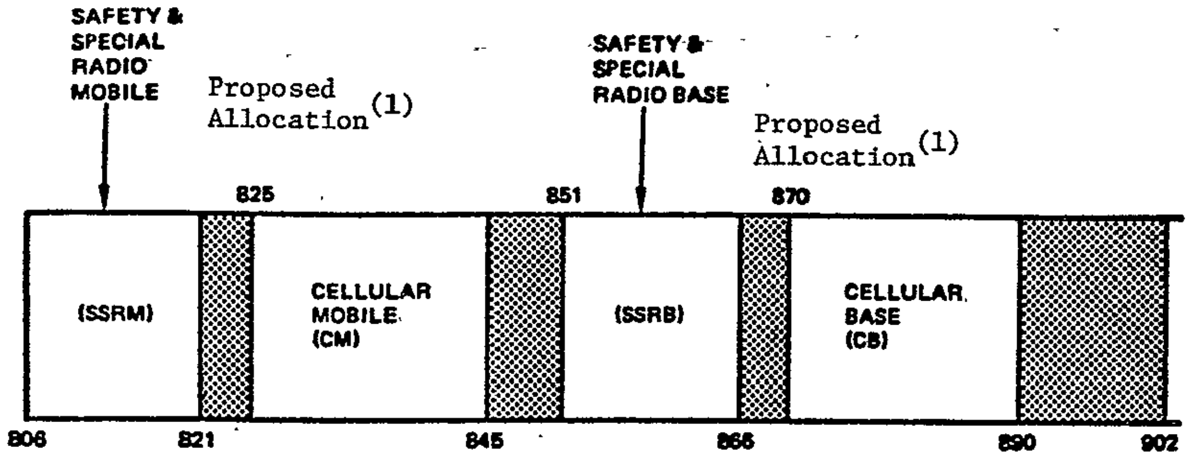
Figure 1-9 shows the current FCC allocation in the high UHF (806 to 902-MHz) band. As depicted in the figure there are four reserve bands. The assumption for this study is that portions of the reserved bands will be allocated for the mobile satellite service. The assumed allocation consists of a pair of 10-MHz bands for uplink and downlink purposes. Each band consists of a 4-MHz segment and a 6-MHz segment, giving a total of 10 MHz. A 10-MHz band is assumed to be needed to satisfy the channel requirement for the second-generation system. (In an NPRM released in January 1985, the FCC has proposed to allocate a 4-MHz band pair in the UHF for MSS. The impact of a smaller allocation, say 4 MHz, will be studied in Chapter 6.) Specifically the assumed uplink allocation is 821 to 825 MHz and 845 to 851 MHz.

The downlink band is 866 to 870 MHz and 890 to 896 MHz.

The above allocation is shown pictorially in Figure 1-10 and will be used for the design of a baseline system, or UHF system.

The alternative system is assumed to be operating in the L-band and is referred to as the L-band system, as opposed to the UHF system. The suitable L-band frequency is assumed to be a 10-MHz segment in the band currently allocated for the Aeronautical Mobile Service, which is 1646.5 to 1666 MHz for uplink and 1545 to 1559 MHz for downlink.

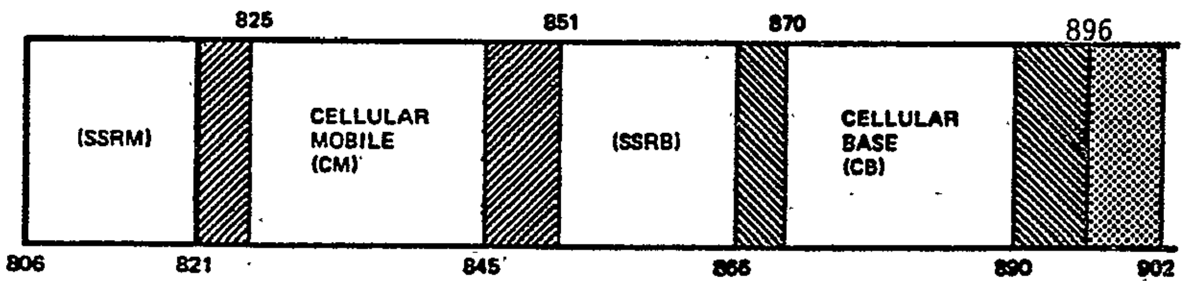
Various frequency bands have been proposed for the backhaul links by the first-and the third-generation systems. Some first-generation systems have proposed to use the UHF band for both the service links and the backhaul links, while others have advocated the use of the Ku-band for the backhaul



(1) In a Notice of Proposed Rulemaking released January 28, 1985, the FCC proposed to allocate on a primary basis the 821 to 825 MHz and 866 to 870 MHz for MSS.

RESERVE

Figure 1-9. Current FCC Frequency Allocation in the 806-902 MHz Band



Mobile Satellite Service (Uplink)

Mobile Satellite Service (Downlink)

Figure 1-10. Assumed Frequency Allocation for the MSAT-2 Study

links. In the 55-m system design, yet another frequency has been assumed, i.e., the S-band. There may be advantages or disadvantages for choosing one frequency band over another. For the second-generation system, the backhaul frequency band is assumed to be the Ku-band. In specific, the uplink and downlink frequencies are 13.2 GHz and 11.65 GHz, respectively.

The required bandwidth is assumed to be 50 MHz, centered at the above frequencies. The 50-MHz band is required to avoid the necessity of employing multiple backhaul beams.

Although a 10-MHz band is assumed to be available for the service links and the frequency reuse scheme is anticipated, there will still not be enough satellite channels to accommodate all the projected users (see Chapter 2 for market projection). To pack as many channels as possible into the 10-MHz band, a combination of narrowing the channel spacing and the use of a spectral efficient modulation is needed. A channel spacing of 5 kHz is assumed. Comparing to the 30 kHz used in the cellular system, this will result in a six-fold increase in channels for the same amount of allocation. The required modulation scheme is discussed in the next paragraph.

1.5.4 Modulation Scheme and Data Rate

The 5-kHz channel spacing dictates the use of a spectral-efficient modulation method. There are many such schemes but Gaussian baseband filter minimum-- shift-keying (GMSK) is considered as the one with the potential and is being studied extensively by MSAT-X.

Using a 5-kHz channel and GMSK modulation, recent studies (Appendix A) have shown that satisfactory adjacent channel interference can be obtained at a data rate of 2400 bps. Without exploring the sensitivity of the system capacity (i.e., the amount of traffic) to the data rate and channel spacing, it is assumed that 2400 bps will be sufficient for all services to be provided by the system, possibly excluding digital voice. Although both analog channels and digital channels can be supported by the satellite, it is assumed that all services will be in digital form for the second generation. A vocoder will therefore be needed in the mobile terminal that provides mobile phone service. At present, toll quality digital voice at 2400 bps is not achievable. It is assumed however that the quality will be improved by the year 1990, or that a higher data rate will be used to improve the quality of digital voice, and some means to support the higher data rate using the same 5-kHz channel spacing will be found.

1.5.5 Channel Multiplexing and Multiple Access Scheme

The second-generation system is assumed to employ SCPC-FDM-DAMA schemes, as mentioned in Section 1.2.4.

1.5.6 Mobile Antenna

Various types of mobile antennas have been mentioned in [1, 3, 4, 5, 6, and 7], with nominal gain ranging from 4 dBi to as high as 16 dBi. The proper design of the mobile antenna is important to the success of a mobile satellite system. A high-gain mobile antenna would ease the burden on the spacecraft, but such an antenna is very likely to be extremely expensive to implement on

mobile vehicles. A low-gain antenna such as a 4-dBi antenna will be much less costly to implement, but the use of this type of antenna would place a tremendous burden on the satellite to provide the needed EIRP to satisfy the link requirement. Consideration should therefore be given to both the cost and performance in selecting a particular type of mobile antenna.

For application to the second-generation mobile satellite system, a medium-gain antenna (MGA) is chosen for the mobile terminal with a gain of 10 to 12 dBi. The low-gain antenna (LGA) with a gain of 4 to 6 dBi is excluded because it would place an unrealistic requirement on the satellite EIRP. The impact of employing a LGA will be examined in Chapter 6. The high-gain antenna (HGA) with a gain of 16 to 20 dBi is not considered for two reasons. First, the HGA is transportable but not suitable for mobile vehicles because of its size. Secondly, even if the HGA can be implemented on mobile vehicles, it would probably be too expensive to be practical.

The characteristics of the MGA to be used in the study are based on the antenna work performed by JPL under the MSAT-X program. A lot of work has been performed by MSAT-X on both the LGA and MGA. The current work on the MGA focuses on reducing the antenna cost and on the design of a tracking system. The available results on MGA are summarized in Appendix B. Based on work performed to date, a typical mechanical MGA will provide a broad pattern in the elevation direction and a relatively narrow pattern in the azimuth direction. A mechanical MGA will require some kind of tracking mechanism for tracking in the azimuthal direction.

A minimum gain of 10 dBi can be expected for elevation angles ranging from 20 to 60 degrees. This antenna will be capable of switching between right-hand circular polarization (RCP) and left-hand circular polarization (LCP), an important feature that allows the antenna to be operated in a multiple satellite environment using polarization diversity. A typical elevation pattern for the MGA is shown in Figure 1-11 [9].

1.5.7 Mobile Terminal

The mobile terminal is assumed to have the same general characteristics as described in Section 1.2.5. In specific, the mobile terminal is assumed to have a noise figure of 1.5 dB or better, a minimum transmitted power of 10 to 20 watts and a G/T of -17 dB.

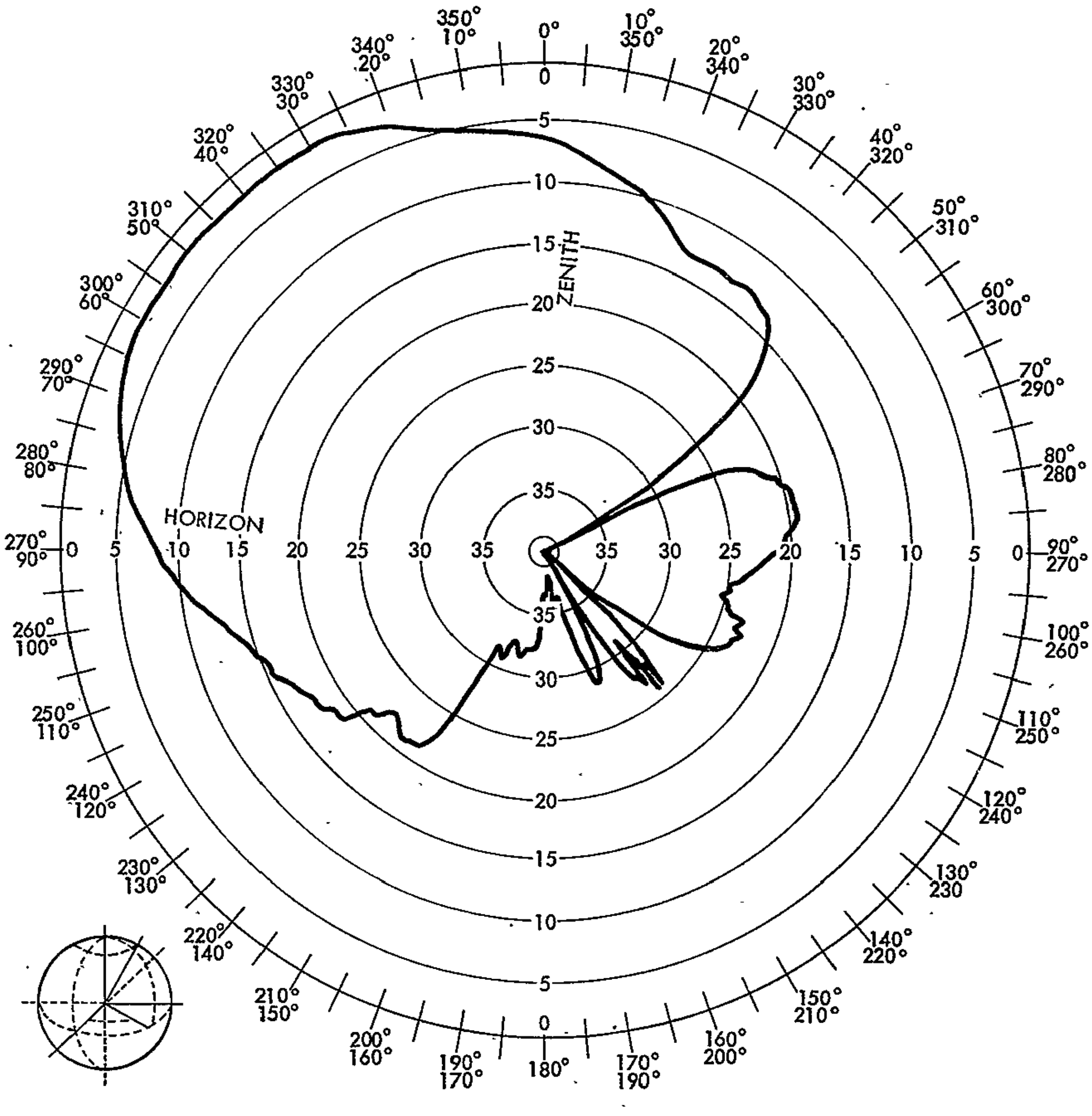


Figure 1-11. A Typical Elevation Pattern for a Medium-Gain Antenna (MGA)

REFERENCES

[1] Mobile Radio Alternative System Study, Volume III, Satellite/Terrestrial (Hybrid) Systems Concepts, John D. Kiesling and Roy E. Anderson, General Electric Company Report WPC-0112M-15M, June 1983.

[2] MSAT-X User Survey, E. Dutzi, JPL IOM 311.3-266/0938C, November 15, 1983.

[3] Land Mobile Satellite Service (LMSS): A Conceptual System Design and Identification of the Critical Technologies, Part II: Technical Report, Edited by Firouz Naderi, JPL Publication 82-19, February 15, 1982.

[4] Application of Mobile Satellite Corporation for Authority to Construct and Operate a Mobile Satellite System to Serve the United States, Filing to the Federal Communications Commission by Mobile Satellite Corporation, March 9, 1983.

[5] Application of Skylink Corporation for Developmental Land Mobile Satellite Services, Filing to the Federal Communications Commission by Skylink, September 12, 1983.

[6] Requirement for A Mobile Communications Satellite System, Volumes 1 and 2, TRW report, April 11, 1983.

[7] Mobile Communications Satellite (MSAT) Communications System Concept Document, Communications Research Center Department of Communications, Shirby Bay, Ontario, Canada, March 2, 1983.

[8] "NASA's Mobile Satellite Communications Program; Ground and Space Technologies," F. Naderi, G. H. Knouse, and W. J. Weber, presented at the International Astronautics Federation Congress, Laussane, Switzerland, October 1984.

[9] Concepts and Cost Trade-Offs for Land Vehicle Antennas in Satellite Mobile Communications, Final Report, F 84-10, Ball Aerospace Systems Division, Boulder, CO., July 1984.

CHAPTER 2

SYSTEM DESIGN AND TRADE-OFF

2.0 INTRODUCTION

A mobile satellite system or network contains a space segment, which has one or more geostationary satellites, and a ground segment, which includes the mobile terminals, gateways, base station, etc. The design of the system consists of a series of trade-offs of various parameters at both the system and subsystem levels. The parameters being traded may be entirely within one segment of the system, such as the satellite system, or between the two segments, i.e., both the satellites and the mobile terminals. The normal earth-station EIRP vs. satellite G/T, and satellite EIRP vs. earth-station G/T trade-offs are not straightforward for the mobile satellite system because of its unique characteristics, including the multiple beams and frequency reuse features. The interrelationships between various parameters are complex and their impact on the system in terms of its cost and performance are sometimes not obvious; however, they often directly or indirectly affect the system. Consequently, it often is not possible to trade one parameter with another without considering the indirect effects on other parameters, which may ultimately determine the outcome of the trade-off. For example, one may not simply trade the mobile terminal EIRP with the satellite G/T without considering the effects on the rest of the system. A different antenna size changes the number of multiple beams and, hence, the frequency reuse factor and the number of required transponders. The frequency reuse factor may in turn affect the required antenna sidelobe level, which may eventually dictate the design of the antenna feed. The number of transponders affects the payload weight, and subsequently may impact the spacecraft power and the capacity of the system. All of these items may drastically alter the system's performance and cost. Thus,

many trade-offs necessarily involve more parameters than expected. The primary objective of the study, as mentioned in Chapter 1, is to produce a viable second-generation mobile satellite system concept, with emphasis on the satellite design. The design of the ground segment will be derived from the MSAT-X work. With this ground rule in mind, all trade-offs and designs will be focused on the spacecraft. The ground segment will be considered only when it directly and significantly affects the design of the satellite or the total system performance, or when it is explicitly stated in the secondary objectives. The various parametric trade-offs and designs will be addressed following a brief description of the trade-off criteria. The results of the trade-offs will lead to a baseline system design (i.e., the UHF system), which will be presented in Chapter 3.

2.1 TRADE-OFF CRITERIA

One of the reasons for NASA's involvement in the mobile satellite service is to promote the development of a commercial system through the private sector. NASA does not intend to build, launch, or operate a mobile satellite system. Any system, if and when deployed, will be commercially oriented. A commercial system must be economically viable. Consequently, cost should be a major factor to be considered in the design of the system, in addition to other factors such as technology maturity and reliability.

The cost consideration poses several questions that need to be addressed. A mobile satellite system consists of many elements and not all of them are owned by a single entity. One possible example is as follows: The system operator, after obtaining a license from the FCC, builds, launches, and operates the satellite. He has to build the NMC's and TT&C (Tracking, Telemetry, and Command) stations, but he probably will not sell the service directly to

the end users. Instead, he may sell the service to independent, third-party operators, who in turn sell the service to the end users for a profit. The third-party operators have to build their own gateways and the end users will either purchase or lease the mobile equipment. In this scenario, whose cost should be used as a figure of merit? Should it be the total system cost, the user cost, or the cost of a particular element such as the satellite? And more importantly, can the cost factor be considered independent of the performance of the system or its capacity? (The system cost is the cost of the entire mobile satellite system, including necessary maintenance and operation, but excluding the cost of the mobile terminal. A more detailed discussion is provided in Chapter 6.)

Minimizing the total system cost does not necessarily imply a minimum user expense because each element in the network contributes differently toward the user cost due to different equipment lifetimes and replacement and operation costs. Since all expenses must eventually be paid for by the end users, it is reasonable to utilize the user cost as a measure of the efficiency of the design. However, user cost is highly dependent on the system capacity, due to the economics of scale, as demonstrated in [1]. User cost alone would not be a sufficient criterion for identifying a good design. Instead, both user cost and system capacity should be considered.

The series of trade-offs in the following sections use the above criteria with the goal of satisfying the system requirements set forth in Chapter 1. To facilitate the trade-off study, a computer program has been developed to calculate the user cost. A description of the program is provided in Appendix C. The computation of the user cost involves the estimation of the price of various elements in the network, the inflation rate, the

investment return, etc. Because there is a degree of uncertainty in estimating these parameters, the cost data should therefore be applied subject to judgment.

2.2 NUMBER OF SATELLITES

The number of satellites and their locations are important system parameters that need to be determined. Most of the first-generation systems are planning to employ two satellites to provide service. On the other hand, the 55-m system studied by JPL calls for only one satellite. How many satellites will the second-generation system need? The decision is not arbitrary; instead, it is influenced by a number of factors including market demand, user cost, and mobile antenna characteristics.

2.2.1 Market Demands

A market demand study by General Electric indicates that the total service demand by the year 1990 will range from a conservative 8,217 erlangs to an optimistic 43,437 erlangs, with a likely estimate of 30,104 erlangs (Table 2-1) [2]. The total service demand in the GE study includes the demand of the radio telephone service, which was assumed to be analog voice requiring a bandwidth of 15 kHz. The demand for mobile telephone service was estimated and converted to an equivalent demand for 4-kHz channels. The total service demand is shown in Table 2-2 for the likely case. As indicated in the table, a demand of 12,210, 17,676, and 25,860 erlangs is expected for the years 1990, 1995, and 2000, respectively. Canada was not included in the GE survey; if it had been included, the projected demand would be increased by about 400 by mid-1990's [3]. Assuming a market penetration, which is very conservative, and a channel loading of 1.0 erlang per channel, the required capacity of the satellite system would then be 3,663, 5,302, and 7,759 channels for the three periods.

TABLE 2-1. Total Service Demand, Erlangs (Obtained from [2])

	1990	1995	2000
NEW SERVICES (0.01 ERLANGS PER TRUCK)			
TRUCK TRACTORS (1)	869	959	1059
OIL & GAS	430	498	584
	1299	1457	1643
COMMERCIAL & PUBLIC RADIO (0.01 ERLANGS PER MOBILE)			
CONSERVATIVE	1113	1562	2190
LIKELY	4404	7093	11423
OPTIMISTIC	9760	15718	25314
RADIO TELEPHONE (0.03 ERLANGS PER MOBILE)			
CONSERVATIVE (2)	1548	1975	2521
LIKELY (2)	6507	9126	12800
OPTIMISTIC (2)	8634	13906	19503
CONSERVATIVE	5805	7406	9454
LIKELY	24401	34223	48000
OPTIMISTIC	32378	52148	73136
TOTAL			
CONSERVATIVE	8217	10425	13287
LIKELY	30104	42773	61066
OPTIMISTIC	43437	69323	100093

(1) INTERACTIVE DATA DEMAND FOR TRUCK TRAILERS IS NEGLIGIBLE COMPARED TO VOICE TRAFFIC

(2) CONVERTED TO 4-kHz CHANNELS BY RATIO OF 15/4 = 3.75

Table 2-2. Total Service Demand, Erlangs Based on the Likely Estimate

	1990	1995	2000
New Service, Erlangs	1,299	1,457	1,643
Commercial & Public Radio, Erlangs (Likely)	4,404	7,093	11,423
Radio Telephone, Erlangs (Likely)	6,507	9,126	12,800
Total Service Demand, Erlangs	12,210	17,676	25,866

In order for a satellite system to provide these capabilities, the actual number of channels in the system must be higher. This is because the user distribution is not uniform over the entire coverage area. The user density, i.e., the number of users per beam, varies from one beam to another for a system utilizing constant or near-constant beam size. A system with variable beam sizes, that adjusts its beam size according to the user density, would alleviate this problem. Such a system, however, would be very complex and, hence, is not considered in the baseline design. A study performed by TRW indicates that most of the user population is concentrated in the eastern part of CONUS (see Fig. 2-1) [4]. A satellite system with constant beam size may find the demand of service to be very high for the eastern beams and very low for the mid-west beams, thus reducing the effective capacity of the satellite system. To recognize this fact, the required capacity will be assumed to be twice the service demand, resulting in a channel requirement of 7,326, 10,605, and 15,519 channels for 1990, 1995, and 2000.

In order to determine the number of satellites required to meet the projected channel demand, it is necessary to estimate the number of channels each second-generation mobile satellite would have. From the spectrum point-of-view, a 10-MHz allocation (i.e., 10 MHz up and 10 MHz down), in theory, could accommodate a very large number of channels depending on the frequency reuse and the number of multiple beams. For example, a 24-beam satellite would be able to provide about 7,000 channels of 5 kHz each for a frequency reuse factor of 7, and about 12,000 channels for a frequency reuse factor of 4. (The frequency reuse factor is simply the number of frequency subbands that the allocated band (10 MHz) is divided into in order to reuse the frequency. See Section 3.11 for more information.) The number of channels can be calculated according to the following formula:

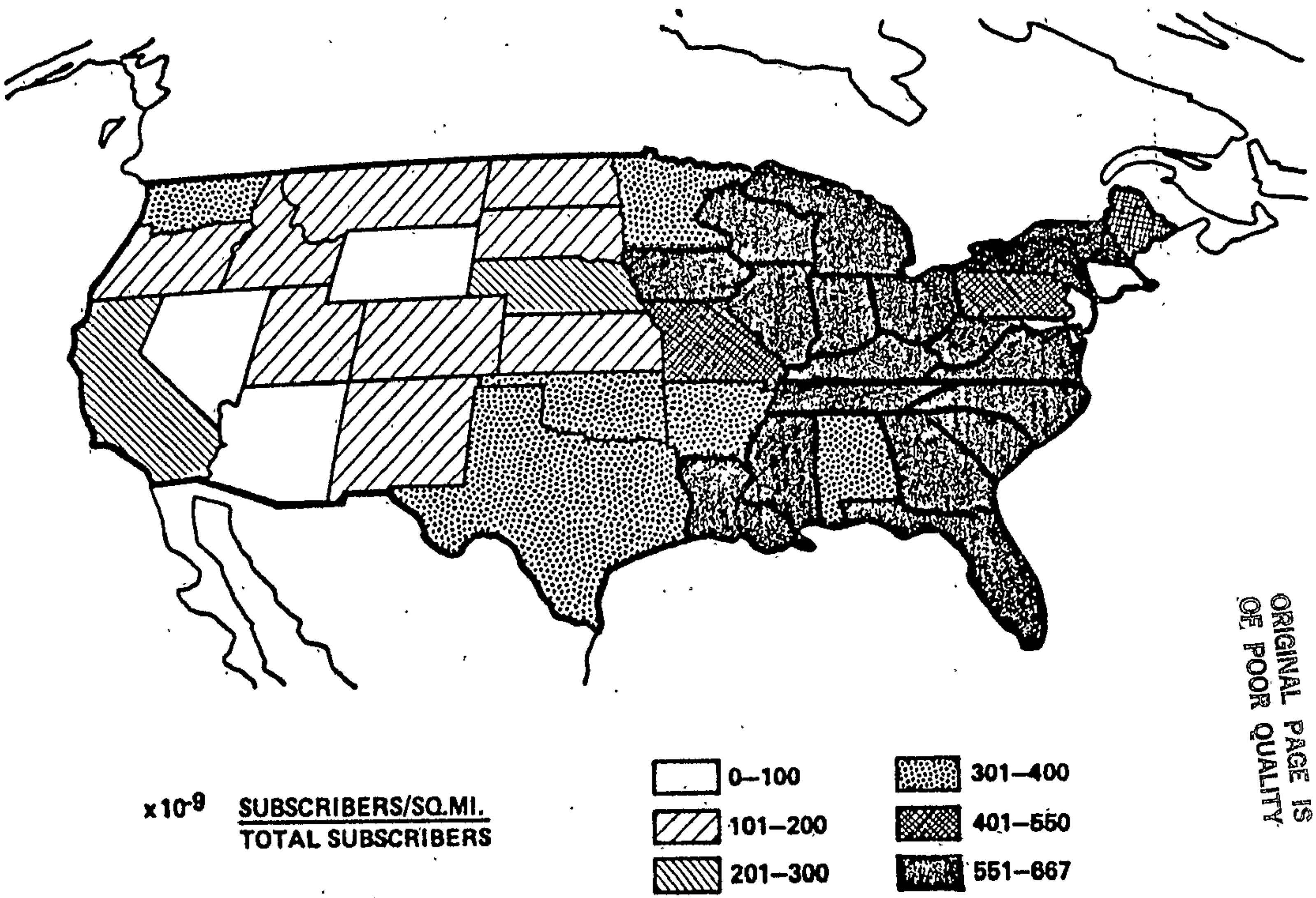


Figure 2-1. Geographic Subscriber Distribution

(No. of channels) = (No. of Beams)·(10 MHz)/((5 kHz)·(Freq. Reuse Factor))

From the above calculation, it would seem one satellite would be adequate. However, practical limitations such as satellite size, weight, and power prevent this from happening. The number of channels is expected to be far less than 7,000 for a practical second-generation mobile satellite. To satisfy this channel requirement with a single satellite would need a third-generation satellite with a customized bus, not the second-generation bus. Based on a survey of three commercial satellite manufacturers, the number of channels that can be expected from the next-generation high-power communications satellites is roughly in the neighborhood of 2,000-5,000 channels. Although this is far less than the capacity of the third-generation system, it represents a big increase over the first-generation system which has a capacity of only a few hundred channels.

Assuming 4,000 channels per satellite, the number of satellites required to meet the projected demand would be between one and two for 1990, slightly more than two for 1995, and more than three for 2000. Since the second-generation system will be operating in the 1990 to 2000 time frame, the number of satellites required would range from one, in the beginning, to three, at the end. The projected service demand and number of satellites are tabulated in Table 2-3 for the time frame assumed for MSAT-2. The number of satellites is based on 4,000 channels per satellite. From the table, a one-satellite system with 4,000 channels would provide only about 55% (4,000/7,326 = 0.55) of the needed service in 1990, 38% in 1995, and only 26% by the year 2000. In other words, there would be 45%, 62%, and 74% of the users needing but not getting the service. A two-satellite system would have adequate capacity for the early part of the mission but

Table 2-3. The Number of Satellites Required to Meet the Projected Service Demand

	1990	1995	2000
Total Service Demand, Erlangs	12,210	17,676	25,866
Req'd MSAT Capacity, Erlangs (Assuming an average 30% market Penetration)	3,663	5,302	7,759
Req'd MSAT Capacity, Channels (Assuming 1.0 Erlang/Channel)	3,663	5,302	7,759
Actual Satellite Channels Req'd to Provide the above capacity, channels[1]	7,326	10,605	15,519
Number of Satellites required[2]	2-	2+	3+

Notes:

(1) The number of actual satellite channels is twice the required MSAT capacity. The factor of 2 accounts for the skewed user distribution.

(2) The number of satellites required is based on the assumption that each satellite provides 4000 channels.

would not have enough capacity during the later part of its life. On the other hand, a 3-satellite system would have excess capacity for more than half of the operation period. Although Table 2-3 probably provides enough information in determining the number of satellites, other factors should be examined before the final choice is made.

2.2.2 Cost Consideration

Market demand is not the only factor that determines the number of satellites required for MSAT-2. The system cost, as mentioned before, is also a factor. According to a TRW study, the user monthly service charge (MSC) can be reduced by increasing the number of satellites and reducing the spacecraft antenna size, while maintaining the same total system capacity [4]. For example, a system capable of supporting 180,000 users and using a 31-meter antenna and 1 satellite would have an MSC of $241 for a 10% rate of return, while another system having the same capacity but using 2 satellites and a smaller antenna (22 m) would reduce the MSC to $210. One of the factors that contributes to a lower user cost in a multiple satellite system is that its spare satellite accounts for a smaller percentage of total cost. For example, in a system with one active satellite and one in orbit spare, the redundancy is 100%. For a system with two active satellites and one spare, the redundancy is only 50%.

In the TRW study, various cases were examined using a different combination of frequency allocation (4, 10, or 20 MHz), antenna size, rate of return, and number of satellites (1, 2, or 3). For all those cases examined, the MSC is lower for systems using more satellites and simultaneously reducing the antenna size by a proper factor, while holding constant all other variables. Table 2-4 summarizes these results. The MSC is provided in

Table 2-4. Comparison of Relative Monthly Service Charge

a) 10-MHz Allocation(1)

Case No.	5	7	3B(2)	3A(2)
Antenna Size, m	31	22	37	30
No. of Satellites	1	2	2	3
MSC, Relative Ranks	3	1	7	4-6(3)

b) 20-MHz Allocation (shared)(1)

Case No.	9	10
Ant. Size, m	35	24
No. of Satellites	1	2
MSC, Relative Ranks	4	2

c) 4-MHz Allocation(1)

Case No.	6	8
Ant. Size, m	51	36
No. of Satellites	1	2
MSC, Relative Ranks	8	5-6(4)

(1) The 4-MHz allocation consists of a pair of bands of 4 MHz each, with 4 MHz for uplink and 4 MHz for downlink, giving a total of 8 MHz. Similarly the 10-MHz and 20 MHz allocations refer to an allocation of 20 MHz and 40 MHz, respectively.

(2) Cases 3A and 3B are cellular compatible while all others are not. Cases 3A and 3B should not be compared with Cases 5 and 7.

(3) The ranking ranges from 4 to 6 depending on the rate of return.

(4) The ranking ranges from 5 to 6 depending on the rate of return.

Table 2-4 in terms of the relative ranking, with 1 being the lowest and 10 being the highest. The case numbers in the table are exactly those used in [4]. A total of 10 cases were examined by TRW, only eight cases are included in the Table. Cases 2 and 4 are not included because a different requirement had been used. As previously mentioned, if one satellite were to provide the needed capacity, a satellite similar to the third-generation system would be necessary. Such a system would be technically impractical in the second-generation time frame.

2.2.3 Mobile Antenna Isolation

The number of satellites that can be simultaneously operating in the same frequency depends to a large extent on the spatial discrimination and cross-polarization isolation of the mobile antenna. For a low-gain antenna, multiple satellite operation is generally not feasible because of the poor spatial isolation. In a two-satellite operation, a typical medium-gain antenna can be expected to provide 15- to 20-dB of isolation including polarization diversity. For a three-satellite operation, the isolation can be as low as 10 to 12 dB, depending on the locations of the satellites and the design of the antenna. This level of isolation is inadequate because the interference environment is very severe for a mobile satellite system. From an interference point-of-view, a three-satellite system is less desirable. (It is noted that additional isolation can be obtained by staggering the channels, i.e., offsetting the channels of one satellite with respect to the other. For a 2-satellite operation, an improvement of about 5 dB is estimated. For a 3-satellite case, the improvement is expected to be insignificant. The only way to further increase the isolation is to increase the channel spacing or the guard-band, which reduces the utility of the spectrum and hence is not considered.)

Considering all of the above factors, a two-satellite system should be employed. One additional advantage of a two-satellite system over a one-satellite system is that it can provide position location service. The locations of the satellites will be determined in the following section.

2.3 SATELLITE LOCATIONS

The primary factors that determine the satellite locations are the service area, the satellite-mobile elevation angle, and the intersatellite interference. The service area is part of the system's requirements. The elevation angle and intersatellite interference are derived from other system or subsystem requirements. In a multiple satellite system, it is desirable to have as much service area as possible simultaneously covered by two or more satellites, while maintaining a high elevation angle. The high elevation angle is to ensure quality service without placing unrealistic restrictions on the mobile antenna design, or overburdening the power system of the satellite. The desirability for overlapping service is to achieve reliability, so that in case of a failure of one satellite, its service can be readily assumed by the other. For a two-satellite system, this means each of the satellites should be able to service the entire area. The service area considered for MSAT-2 includes CONUS, Alaska, and Canada. This is a widespread area covering about 110 degrees longitude. To have a satellite covering this wide area while maintaining a high elevation angle is not possible; some compromise must be made. Since most users are in CONUS, the selection is expected to favor CONUS.

In selecting orbital locations, consideration must also be given to the potential intersatellite interference. Although the required orbital separation

between two adjacent satellites is a function of the amount of acceptable interference, the mobile antenna characteristics, etc., a separation of 30 to 40 degrees is generally adequate to reduce the interference to an acceptable level, based on a medium-gain mobile antenna having a gain of 10 to 12 dBi. The acceptable interference level will be discussed in Section 2.8.

Considering all the above factors and assuming an orbital separation of 40 degrees, the locations of the two satellites are selected at 90 degrees and 130 degrees west. A contour of a constant 10-degree elevation angle is shown in Figure 2-2 for the satellite at 90 degrees and in Figure 2-3 for 130 degrees. It can be seen from these Figures that the satellite at 130 degrees west will provide good coverage for CONUS, with a minimum elevation angle of 10 degrees in Maine, and for most of Alaska. The satellite at 90 degrees will provide good coverage for CONUS and Canada, but very poor coverage for Alaska.

2.4 SELECTION OF CANDIDATE BUSES

The projected market demand for MSAT-2 ranges from 7000 to 15000 channels. Providing such a capacity by using two satellites implies that the satellite bus must be high power and capable of supporting a fairly heavy payload. A customized bus undoubtedly could provide the needed capability; however, it will probably not be cost effective. Recent developments in satellite communications have prompted satellite manufacturers to develop a more powerful class of buses. This class of buses would probably be more economical if they could be applied to MSAT-2 with minimal modifications. A survey of satellite manufacturers, including Hughes, Ford, and RCA, has indicated that

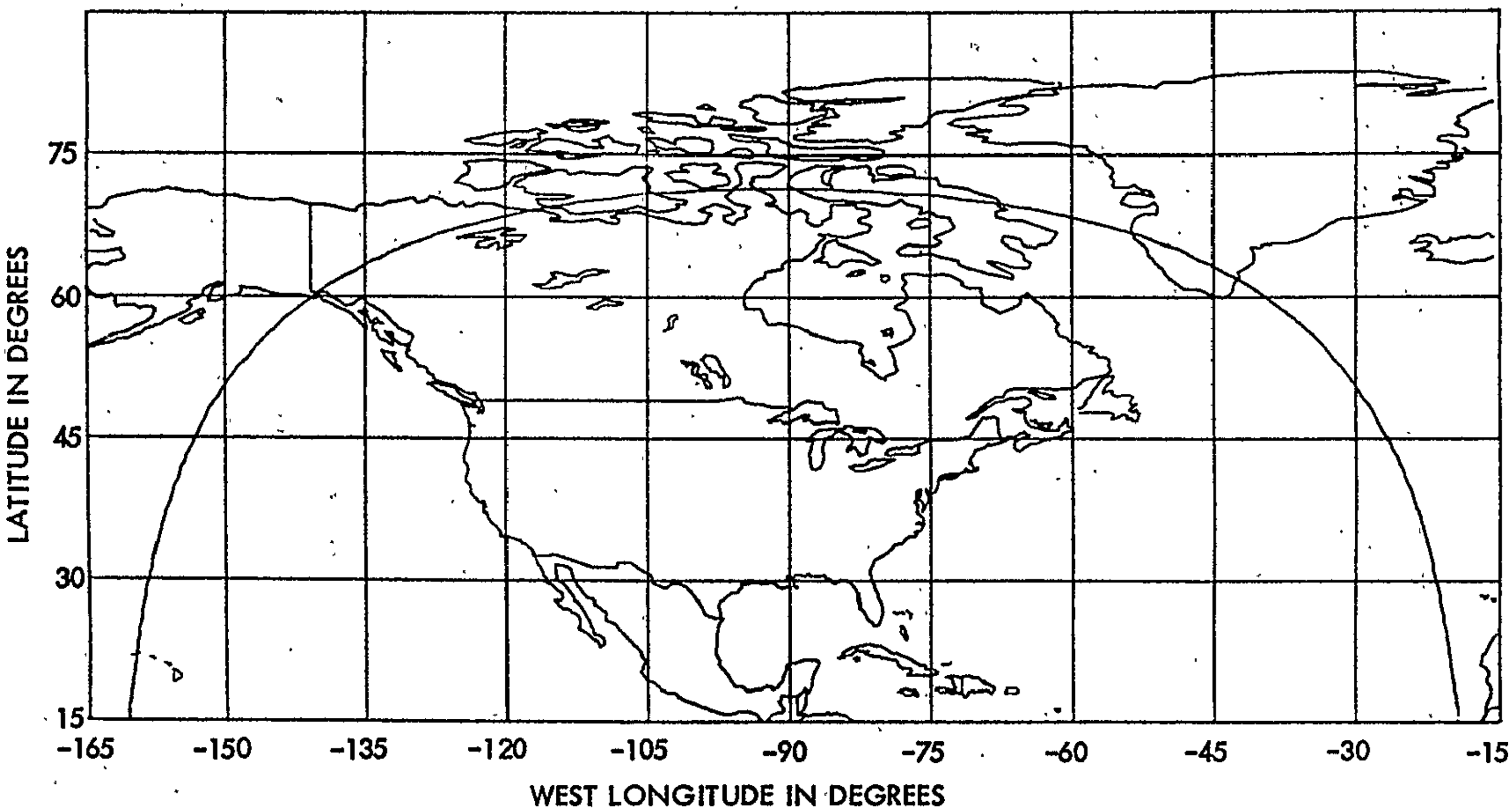


Figure 2-2. Contour of a 10-Degree Elevation Angle for a Satellite at 90 Degrees West

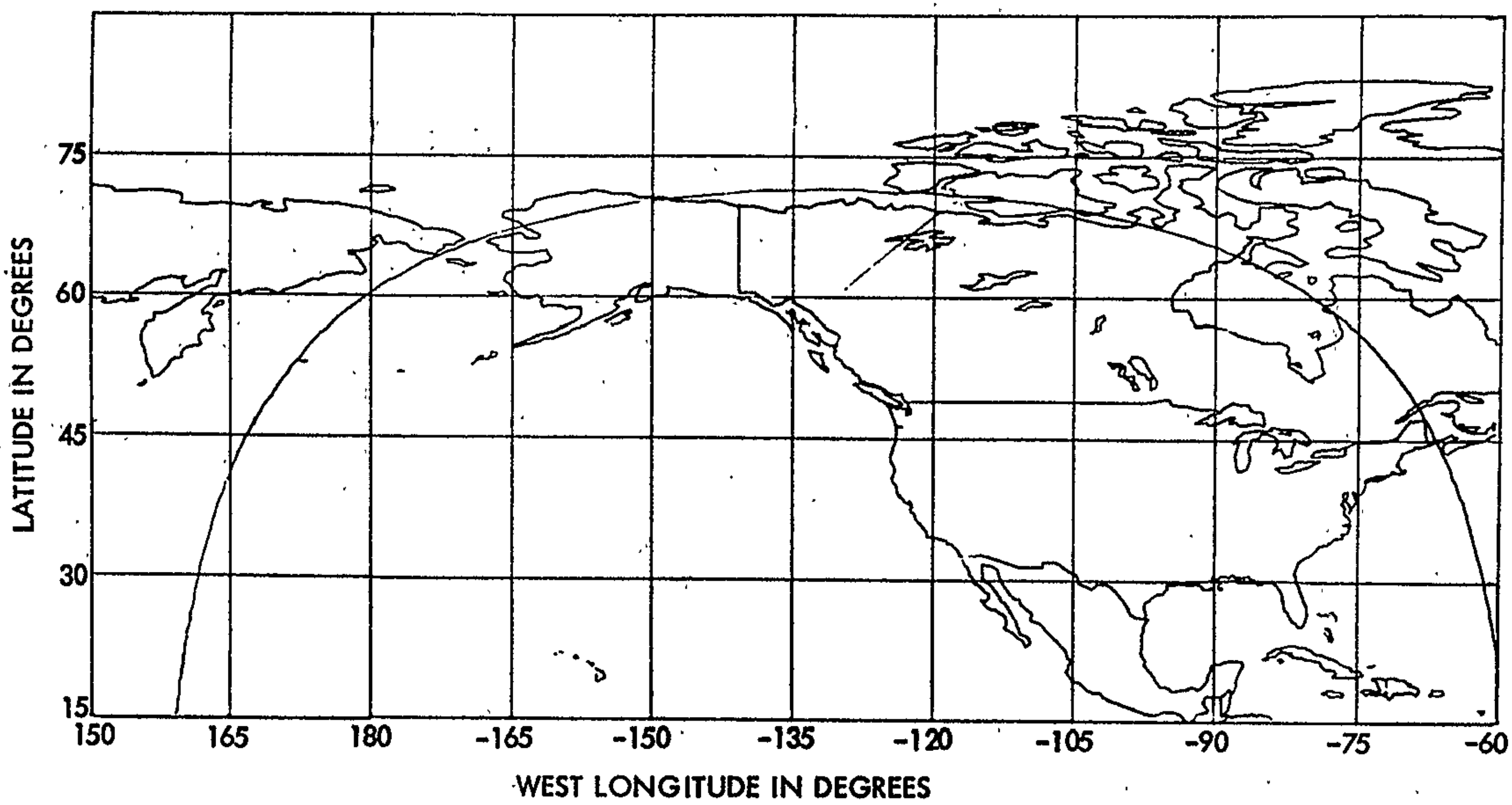


Figure 2-3. Contour of a 10-Degree Elevation Angle for a Satellite at 130 Degrees West

the next-generation, high-power, communications satellite bus being developed by these companies would roughly have the range of capability needed for MSAT-2 and would become commercially available in time for MSAT-2 application. Brief descriptions of three of these buses are given below. (Satellites being developed by other companies may also be applicable to MSAT-2. The fact that only three satellites are described does not preclude others from future considerations.)

The satellite that is being developed by Hughes and is of interest to MSAT-2 is the HS-394. This satellite utilizes a new concept that is different from conventional satellites built by Hughes -- it employs both spin and 3-axis stabilization techniques. It has a cylindrical array which is attached to the main body and a rigid solar array that spans about 35 meters. The cylindrical array produces about 400 watts of power for housekeeping. The rigid solar array can produce about 4000 watts. The bus is designed to be STS compatible and will occupy 1/4 of the shuttle bay. Figure 2-4 shows a conventional Hughes satellite HS-393 and the high-power HS-394.

The one being developed by Ford is 3-axis stabilized. The design of this satellite is based on a modular concept, which allows a customized communications module to be added on easily. The satellite is also shuttle compatible. Figure 2-5 shows the satellite and its STS launch sequence.

The RCA series-4000 high-power satellite shown in Figure 2-6 employs a special design for the propulsion subsystem: shuttle-compatible orbital transfer subsystem (SCOTS). SCOTS is capable of delivering a payload of 4000 to 6000 lbs to the geostationary transfer orbit (GTO). The first SCOTS is expected to become available in 1986 [5]. Series 4000 is also shuttle compatible and its

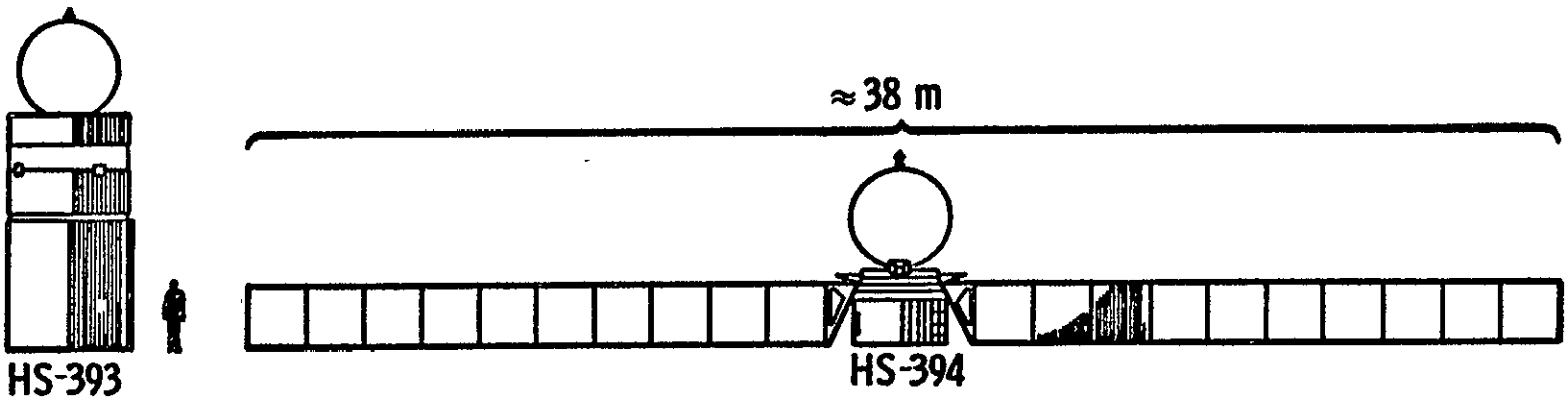


Figure 2-4. Hughes HS-393 and HS-394

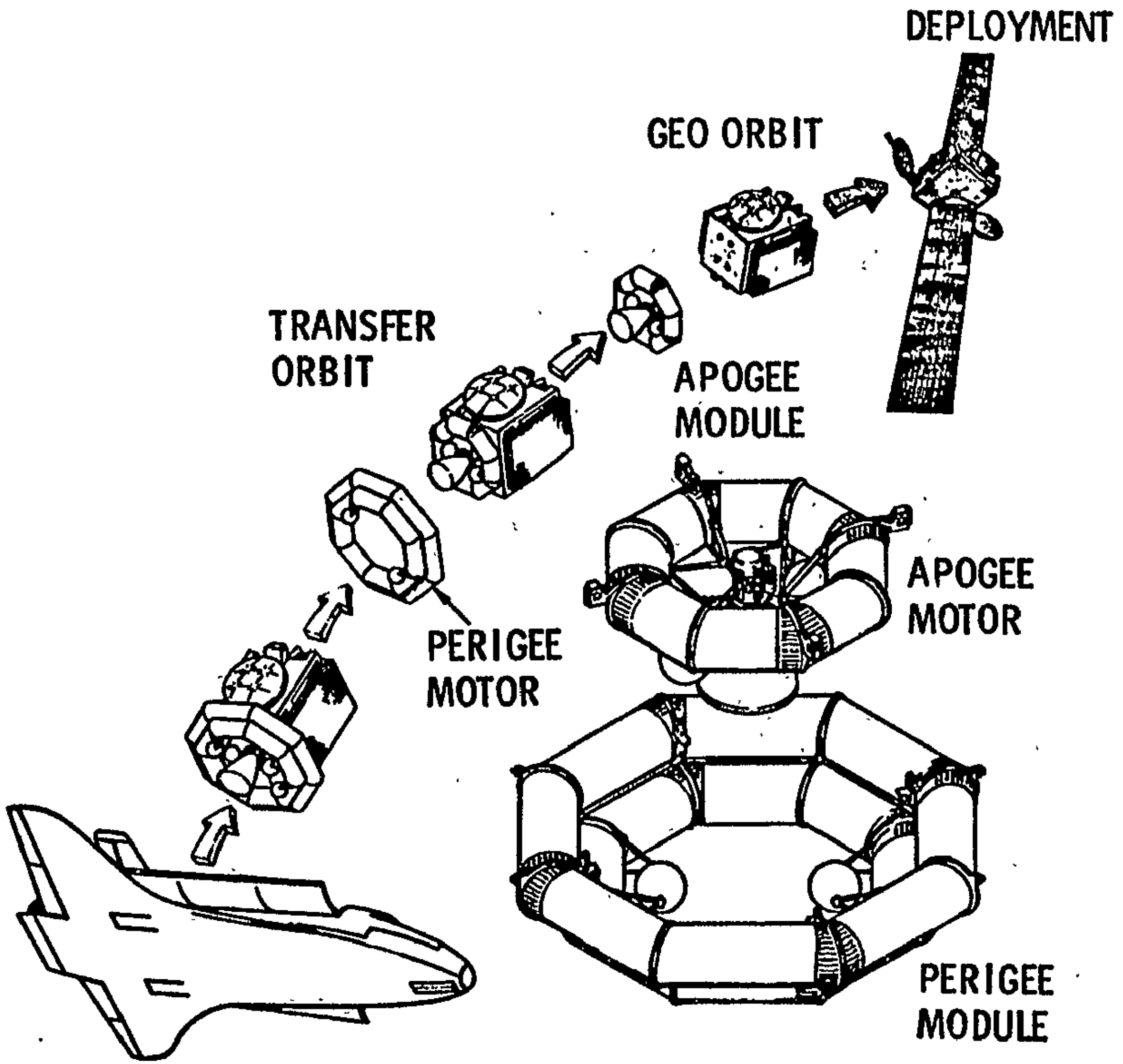


Figure 2-5. Advanced Communications Satellite Bus Being Developed by FACC

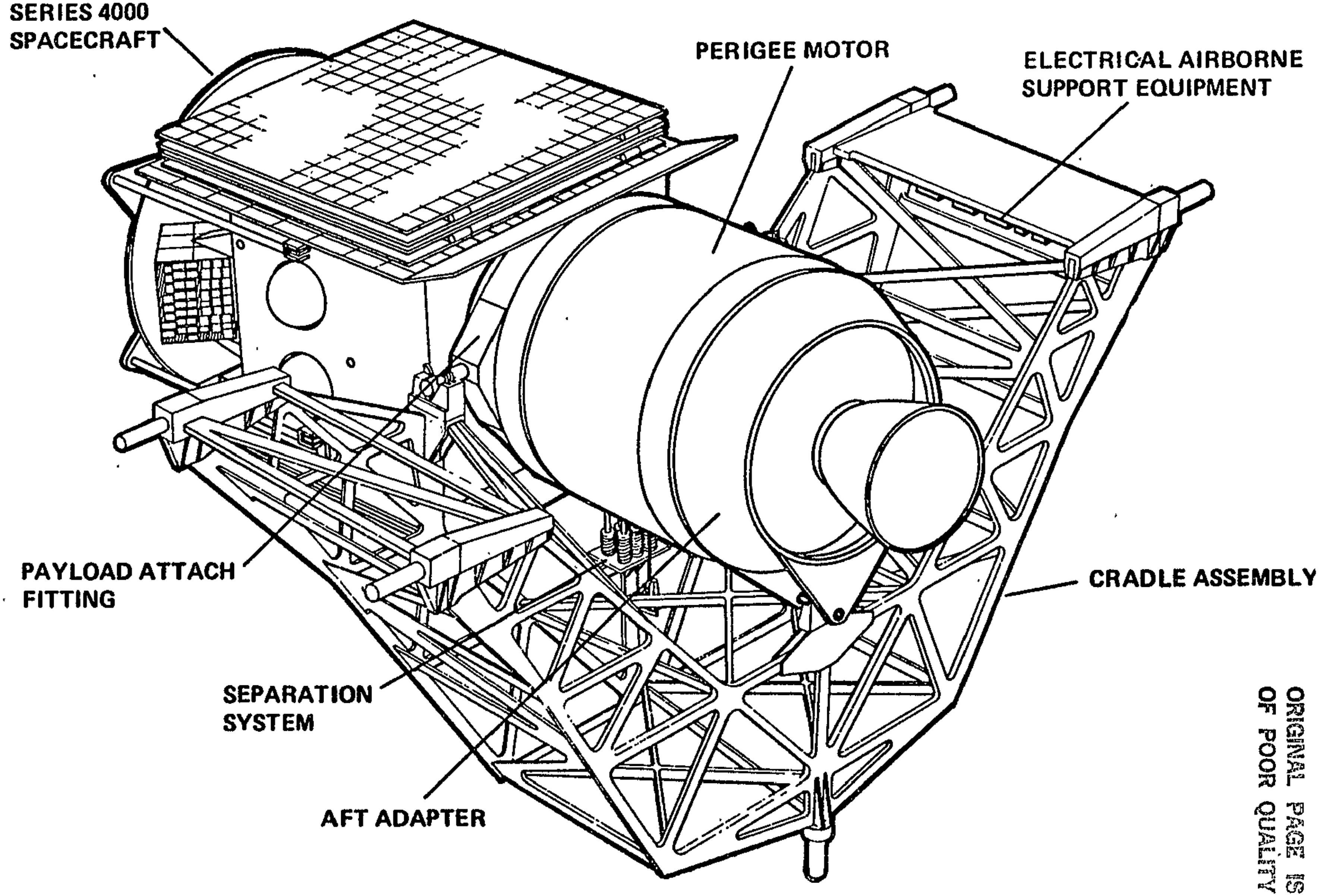


Figure 2-6. Integrated RCA Series 4000/SCOTS Configuration

design has been optimized for a maximum payload weight-to-cargo bay volume ratio. Figure 2-6 shows the integrated configuration of SCOTS and a series 4000 spacecraft.

All satellite buses surveyed are considered as potential candidates.

For the purpose of this study and in order to facilitate subsequent trade-off studies, it is useful to develop a tool to characterize the general capability of the potential candidate buses without being specifically tied to a particular manufacturer. Toward this end, a set of curves has been developed to characterize the payload power and weight of a typical second-generation mobile satellite bus. These curves are shown in Figure 2-7 and are based on currently available data. For a given payload weight, the projected payload power varies over a wide range. The variation arises from: a) the difference between the manufacturers and b) possible future improvements and/or deviation. The nominal capability represented by the center curve will be used as the capability of the baseline satellite bus and will be utilized in antenna sizing. Roughly, the baseline bus is capable of supporting up to about 500 kg of payload or of generating up to 4 kW of payload power.

Implicit in Figure 2-7 are a full eclipse and a full station-keeping capability. A higher payload power or a heavier payload would be possible at a reduced eclipse and/or station-keeping requirement.

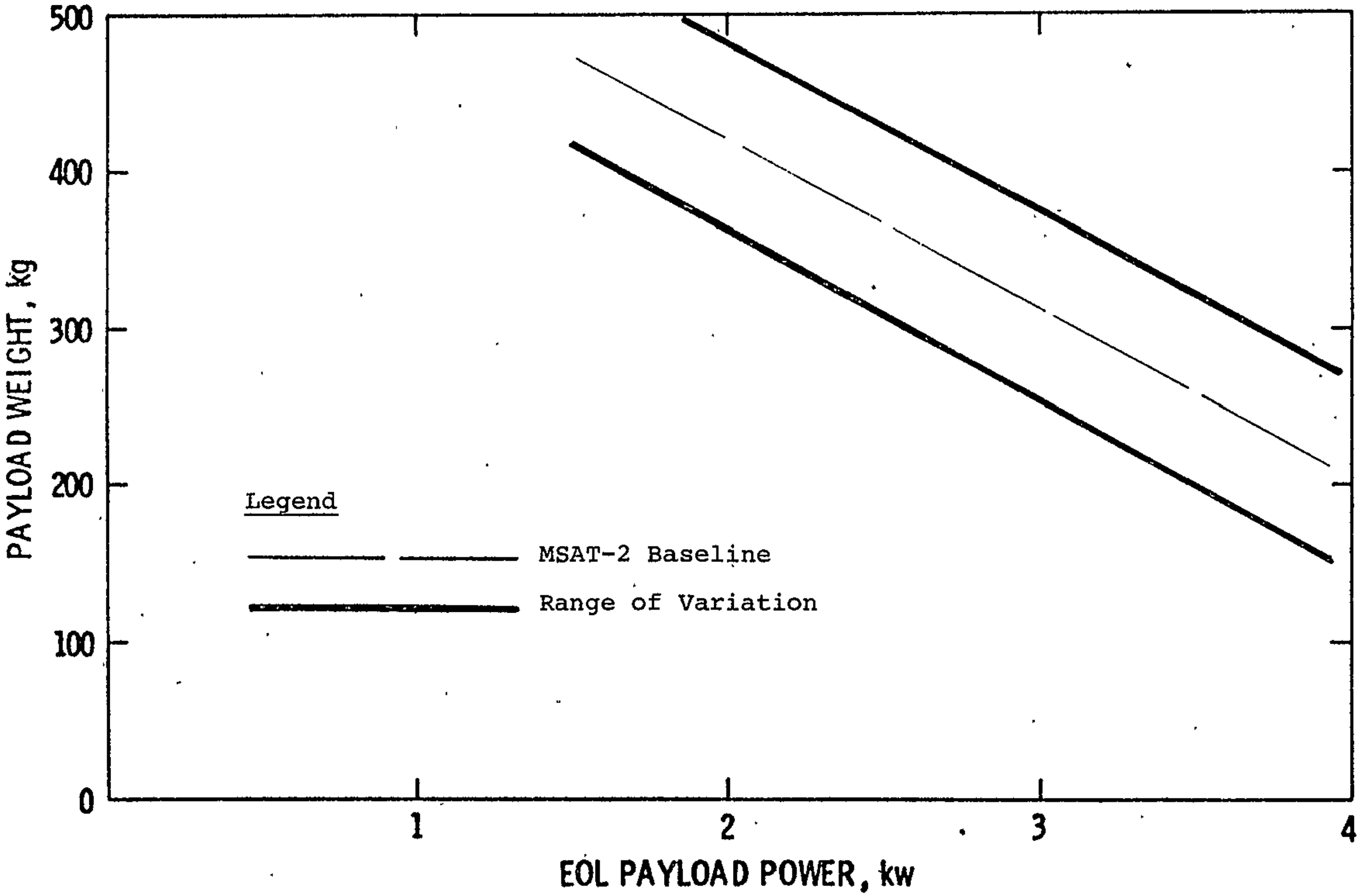


Figure 2-7. MSAT-2 Baseline Payload Weight Vs. Payload Power

2.5 SATELLITE ANTENNA CONCEPTS AND PERFORMANCE TRADE-OFFS

Perhaps the most prominent feature of the mobile satellite is its communication antenna operating at the high UHF or L-band frequencies. The relatively large size of this antenna is due to the following factors:

1) Relatively low frequency (large wavelength)
2) Required high gain to reduce the power requirements onboard the satellite as well as reducing the size and complexity of the ground mobile antenna
3) Small antenna beam size for the purpose of multiple beam coverage of the given area in order to reuse the limited frequency band by spatial diversity.

Appendix G shows the increase in the size of the antenna can be used for reducing the power requirements of the spacecraft and/or increasing the reuse of the frequency band. For the purpose of this study antennas in the 5- to 30-meter diameter range are considered. Due to the complexity of such large antennas from the viewpoint of fabrication, launch, deployment, and electrical performance charac teristics, the selection of an optimal antenna from both mechanical and electrical performance viewpoints is a major task. There are many areas of concern in the design of large,simultaneously operating,multibeam antennas. Since many of these concerns and selection criteria have been addressed in previous studies (see e.g. [6]) here we shall only briefly touch upon those concerns and will concentrate instead on areas which have not been previously addressed in sufficient detail.

2.5.1 Reflector Versus Planar Arrays and Lenses

From electrical (RF) considerations, a wide variety of antennas including reflectors, phased arrays, and lenses can be made to meet the system requirements.

The advantages of a lens or a phased array over a parabolic reflector are the absence of aperture blockage and superior scan performance. The blockage problem in reflector antennas, of course, can be overcome by selecting an offset configuration which leads to structural asymmetry and associated complications. The scan performance of the reflectors can be improved moderately by increasing the focal length, which directly increases the length of the feed support boom and the feed size as shall be explained later.

The major disadvantages of the lens are its weight and the complexity of providing the lens medium. Typically, in lens systems some medium such as dielectrics, artificial dielectrics, waveguides, etc., is needed to focus the rays. Since the extent of the lens medium is the same as the required aperture size in a reflector system, it will weigh considerably more than a lightweight reflecting mesh or membrane which is typically proposed in large spaceborne reflector antennas. A rather lightweight but still fairly complex "bootlace" space-fed lens has been proposed by Grumman [7]. Since no detailed investigation of this system has been performed and no full or scale model exists, it cannot as yet be considered a mature concept. However, it has definite possibilities for applications in the distant future.

Phased arrays offer large and rapid beam scanning, higher (than lens and reflector) aperture efficiency, no spillover loss, coma lobes, or aperture blockage. They also have a higher reliability factor insofar as the failure of a few elements does not affect the overall performance appreciably. On the other hand, due to the complexity of providing multibeam operation with a phased array, requiring an extremely complex beam-forming network, full coverage can be provided by beam steering only (sweeping over the coverage area); simultaneous coverage over the entire area is not feasible. Futhermore, the gain requirements would dictate an

array aperture composed of perhaps thousands of individual radiating elements together with the necessary feeding network. The weight and complexity of such a system is in any case considerable. No mature concepts for configuration, stowage, and deployment of large phased arrays for space applications presently exist. There are, however, several relatively mature, large, single reflector antenna concepts for space applications reviewed in the next section. Multiple reflector antennas (e.g., cassegrainian dual reflector) are not very viable candidates due to additional structural, deployment, and control complexities introduced in exchange for limited electrical performance improvements [6]. Based on the above considerations, a single reflector with an array of feed elements to produce the multiplicity of beams seems to be the most desirable choice, but the question of feed and reflector symmetry must also be considered.

2.5.2 Center-Fed Versus Offset-Fed Reflectors

In multibeam axisymmetric (center-fed) reflector systems, the high-blockage due to the large feed array, feed support trusses, transmission lines, etc., can cause considerable gain loss and sidelobe deterioration. Gain losses of 1.0 to 1.5 dB can be expected in an actual axisymmetric system, while the increase in sidelobe levels is dependent on the initial nonblocked values and could vary from 2 to 10 dB or higher depending on reflector aperture illumination, feed array size and shape, etc. In an actual system with a specific array shape and feed support boom the evaluation of blockage effects is fairly complicated and requires a detailed study. Figure 2-8 shows the offset and axisymmetric reflector configurations where the pros and cons of the two systems are also summarized. In the land mobile satellite system both gain loss (which increases the power requirements of the satellite) and sidelobe increase (which decreases the interbeam isolation) should be minimized. This fact points toward the selection of the offset-fed reflector over the axisymmetric as the baseline configuration.

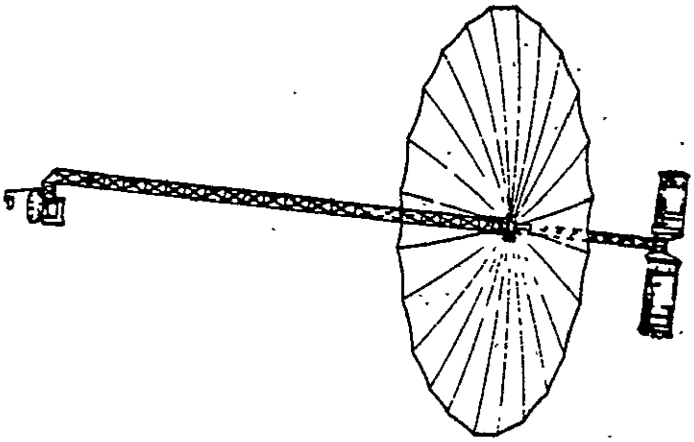
SYMMETRIC REFLECTOR

* HAS ROTATIONAL SYMMETRY
* HAS SHORTER SUPPORT BOOM
* IS STRUCTURALLY SIMPLER
* IS EASIER TO CONTROL

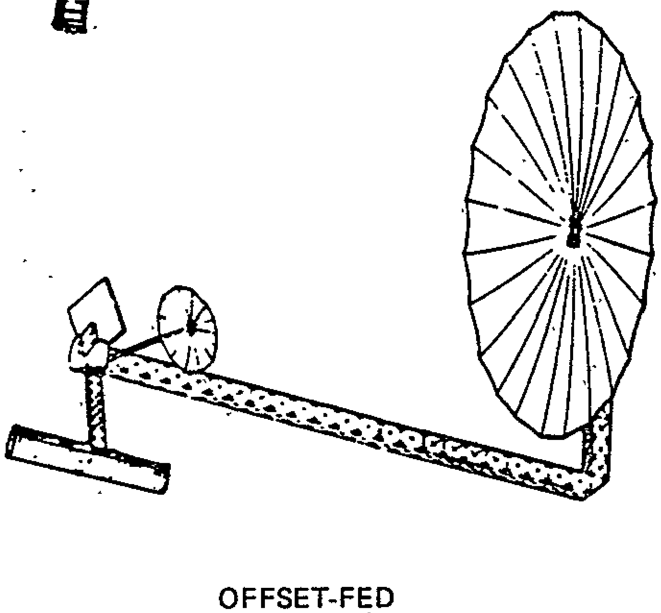
BUT

* HAS HIGH RF BLOCKAGE DUE TO LARGE FEED ARRAY CAUSING GAIN LOSS $\geq$ 0.5 dB

  SIDELOBE DETERIORATION FROM -20 TO -18
  -30 TO -25
  -40 TO -30
* HAS HIGHER SOLAR ARRAY BLOCKAGE REQUIRING - LONGER SUPPORT BOOM
  - LARGER SOLAR PANELS



SYMMETRIC CENTER-FED



OFFSET-FED

Figure 2-8. Axisymmetric vs. Offset Reflector Configuration

2.5.3 Accuracy Requirements of the Large Reflector Antennas

One of the major drivers of the reflector antenna design is the accuracy requirement on the RF reflective surface. Deviations from a perfect paraboloid introduce gain loss and sidelobe increase in the far-field patterns. Basically, these errors are of two different kinds: random and deterministic. Both may be caused by structural tolerances and temperature variations across the aperture in an earth-orbital environment. Deterministic errors, if accurately known, can be exactly computed by reflector scattering programs. Random errors are, in general, more difficult to calculate exactly. Both types of errors can be reduced by high-precision surface design and use of materials with very low thermal expansion coefficients, which, naturally, add to the weight and cost of the antenna. Random errors can be estimated by two statistical parameters. The first one, the RMS surface error, is sufficient to calculate the gain loss. This parameter, together with the correlation length of surface errors, can be used to obtain the average sidelobe level increase. In addition, for a given reflector diameter, the illumination taper on the reflector tempers the effects of the surface errors. Table 2-5 shows the calculated values for some typical cases. According to this table a surface error of less than 1/50 causes a gain loss of less than 0.3 dB and is selected as the surface accuracy requirement. (It is noted that the designed accuracy of the baseline reflector is 1/60, which exceeds the required accuracy slightly.)

The axial defocusing, that is the movement of the feed array towards or away from the reflector creates a phase error in the reflector aperture which results in beam broadening, gain loss, and sidelobe increase. However, our studies have shown that by limiting this movement to plus or minus one wavelength (approximately $\pm$ 0.3 meters at high UHF frequencies) the effect would be negligible.

Table 2-5. Effects of Random Surface Errors on Reflector Gain and Sidelobes. C: Correlation Length of Errors
D: Reflector Diameter

	2 C/D	Initial Sidelobe dB	RMS Surface Roughness in Wavelengths					
			1/20	1/30	1/40	1/50	1/60	1/70
Sidelobe dB	1/40	20	19.9	19.9	20.0	20.0	20.0	20.0
		25	24.6	24.8	24.9	24.9	25.0	25.0
		30	28.7	29.5	29.7	29.8	30.0	29.9
		35	31.9	33.5	34.1	34.4	34.6	34.7
		40	33.6	36.3	37.6	38.4	38.8	39.1
	1/20	20	19.5	19.8	19.9	19.9	19.9	20.0
		25	23.5	24.3	24.6	24.8	24.8	24.9
		30	26.3	28.2	28.9	29.3	29.5	29.6
		35	27.8	30.7	32.2	33.0	33.6	33.9
		40	28.4	32.0	34.1	35.5	36.5	37.2
	1/10	20	18.2	19.2	19.5	19.7	19.8	19.8
		25	20.7	22.8	23.7	24.1	24.4	24.5
		30	22.0	25.1	26.7	27.7	28.3	28.7
		35	22.5	26.2	28.4	29.9	30.9	31.7
		40	22.7	26.6	29.1	30.9	32.3	33.4
	1/5	20	15.2	17.4	18.4	18.9	19.2	19.4
		25	16.3	19.5	21.2	22.3	23.0	23.4
		30	16.7	20.4	22.7	24.2	25.3	26.2
		35	16.9	20.7	23.3	25.1	26.5	27.7
		40	16.9	20.9	23.3	25.4	27.0	28.2
Gain Loss dB			1.71	0.76	0.43	0.27	0.19	0.14

The lateral feed array panel movement in the focal plane (lateral defocusing) causes a shift of the aggregate of multiple beams over the coverage area. Therefore, feed array translation and rotation in the focal plane is limited by the pointing and stability requirements levied on the antenna.

The tilting of the feed array with respect to the reflector has several effects. It causes an imbalance in the illumination of the reflector with the consequent decrease in aperture and spillover efficiency and a commensurate gain loss. Furthermore, the movement of all the feed elements (save the focal-point one) can be decomposed into an axial defocusing and a slight lateral movement. A limit of $\pm 2°$ on the feed array tilt angle with respect to its nominal location is deemed quite acceptable.

In pointing the antenna system towards the earth, an initial error in pointing the central axis of the antenna will cause a corresponding shift in location of all the beams over the coverage area. Thus, if the antenna beam footprints (4-dB beamwidth) completely cover the given area, with no coverage outside the given boundaries, then an initial pointing error towards the north could leave some southern border areas uncovered. However, if the beams are arranged in a manner that a certain amount of extra coverage beyond the boundaries is provided, then a pointing error less than this amount will not result in inferior performance. The upper limit on the initial pointing error, therefore, has to be made on the basis of trading off the control difficulties in achieving the pointing tolerance against the possible extra beams - and associated feeds, electronics and power requirements - needed to provide the extra initial coverage. Accordingly, an initial pointing error requirement of roughly 1/6 of the 4-dB beamwidth is suggested. (It is noted that the achievable pointing accuracy exceeds the requirement, Chapter 3.)

Pointing stability sets a limit on the errors occuring during the operation of the system, due to dynamic disturbances. Again the only problem area foreseen for the system is the boundary of the coverage area where the beam edge shifts and the EIRP is reduced by a certain amount depending on the shift angle. It can be shown that the gain loss is related to the ratio of the shift angle to the 3-dB beamwidth by the approximate formula,

$$dG = -6.4\ (d(BW)/BW) \qquad (2\text{-}1)$$

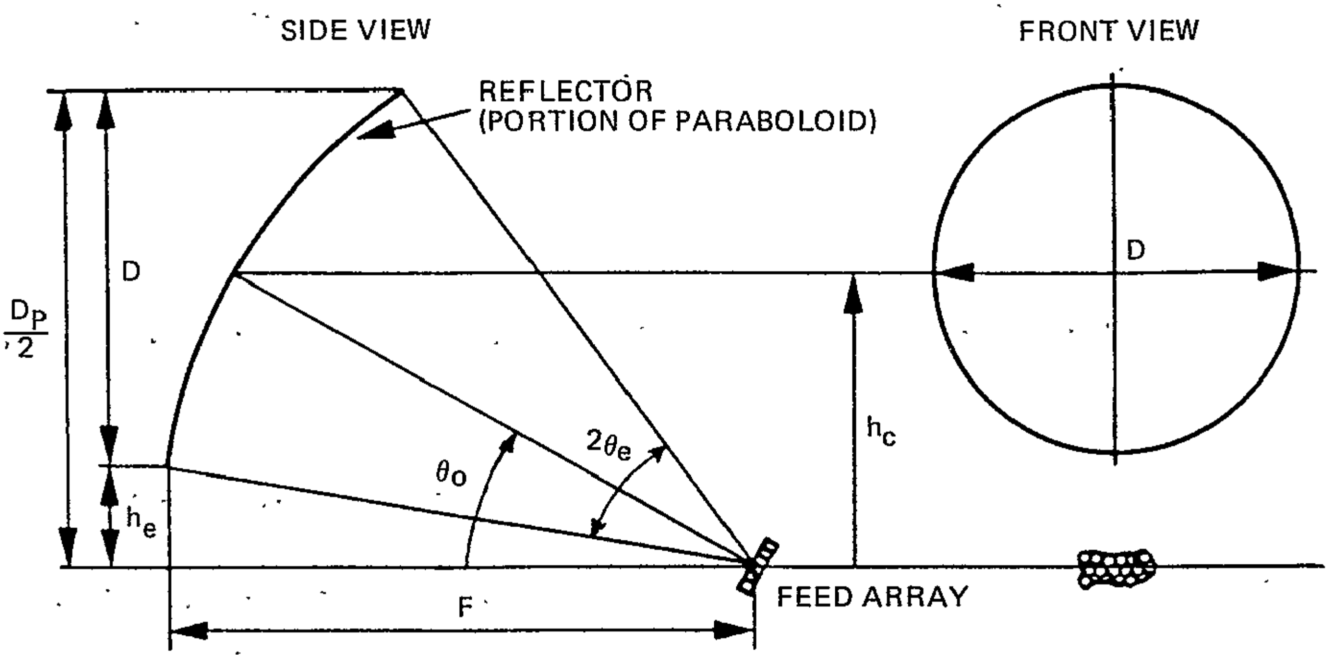
Thus, for example, a 1-dB power margin can accommodate d(BW) = BW/6.4 of pointing stability error.

2.5.4 Characteristics of Baseline Configuration: Offset-Fed Single Reflector

Based on the preceding considerations concerning the relative simplicity of the structure, acceptable electrical performance, and a body of information established in the course of previous studies, an offset-fed single reflector configuration will be considered for the baseline design. The geometric parameters of the antenna are summarized in Fig. 2-9. The main parameters are the diameter, D, the edge offset, h_e, and the focal length, F. All three depend directly or indirectly on the required beamwidth and the total number of beams. Inversely, given the reflector diameter, the beam size, the number of beams, and subsequently the focal length and edge offset height can be determined.

In [6] important design considerations in offset reflector systems have been summarized. In the actual design procedure both simple but approximate formulas as well as rigorous scattering programs are utilized. Here the following general comments are made:

- The beam size decides the reflector diameter (and vice versa). Aperture illumination has a secondary effect on the beam size.



DEFINITION OF PARAMETERS:

F	FOCAL LENGTH OF THE REFLECTOR
D	REFLECTOR DIAMETER (DIAMETER OF THE CIRCULAR PROJECTED APERTURE)
D_P	DIAMETER OF THE GENERATING (PARENT) PARABOLOID
h_c	OFFSET DISPLACEMENT (HEIGHT) OF THE CENTER OF THE REFLECTOR APERTURE
h_e	OFFSET DISPLACEMENT (HEIGHT) OF THE LOWER EDGE OF THE REFLECTOR
θ_o	OFFSET ANGLE
$2\theta_e$	SUBTENDED ANGLE FROM FEED TO REFLECTOR

Figure 2-9. Offset Single Reflector Antenna Parameters

The number of beams decides the focal length. As the total number of beams increases, so does the number of beams scanned from the focus. For maintaining a given performance level in terms of gain and side-lobes, the focal length must be increased as well. As a simple rule the number of scannable beams with a constant performance level increases in proportion to the square of the F/D ratio.

The amount of offset and specifically the edge offset height are dependent on the feed array size, and should be sufficient to allow for the lowest rays reflected from the lower edge of the reflector to clear past the upper edge of the feed array. The feed array size itself, as we shall see in the discussion of the feed array, is a function of the focal length and the angular extent (spatial angle) of the coverage region.

2.6 DEPLOYABLE REFLECTOR ANTENNA STUDY

2.6.1 Introduction

The objective of this study was to obtain design, performance, and cost data for deployable antennas to help assess the technical feasibility, system performance, and cost of MSAT-2. The approach used for obtaining the necessary technical and cost information was to implement study contracts with one or more commercial organizations capable of supplying qualified antenna subsystems that meet the MSAT-2 functional requirements. The contractors selected included Lockheed Missles and Space Co., Inc. for the offset wrap-rib deployable antenna and Harris Government Systems Division for the hoop/column deployable antenna. Limited resources for the MSAT-2 study precluded the acquisition of additional antenna study contracts covering other structural concepts. Since the system level, functional configuration development activity was limited to a single model, both antenna concepts were evaluated, and one was selected as the baseline for the system study.

2.6.2 Antenna Functional Requirements

The antenna aperture size range of 8 to 30 meters dictates the need for self-deployable space structures with mechanical packaging efficiencies, i.e., a ratio of deployed-to-stowed diameter commensurate with the STS. The requirement for an unblocked aperture means that radial-rib and truss-type structures will utilize an offset-feed support structure, while maypole-type configurations will be dependent on using a number of discrete sections of the reflector that are offset from the central column. The antisymmetric reflector surfaces must be capable of highly efficient RF reflectivity up to L-band while maintaining an

on-orbit total surface error of no more than $\lambda/60$. The antenna's structural configurations must be commensurate with the reflector curvature based on F/D from 1.0 to 1.5. The demonstration of technology readiness such as deployment reliability, surface precision, feed support structure alignment, thermal stability, etc., needs to be accomplished by the late 1980's to accommodate a mid-1990's launch.

2.6.3 Deployable Antenna State-of-the-Art

A number of unique mechanical concepts have been conceived for a variety of different types of deployable antennas. The level of maturity of these concepts varies from the disclosure of extremely innovative designs to flight-proven hardware systems. Collectively, these concepts have the potential for accommodating applications involving apertures from one to one thousand meters in diameter for operating frequencies ranging from GHz for small structures to MHz for large apertures.

The potential value of any concept is a function of how well it satisfies a specific application. Typically, deployable antennas are often divided into several categories: mesh and membrane deployable, and precision deployable structures. Mesh deployable-antenna concepts would include maypole, radial-rib, and truss-type structures. Membrane antenna concepts include rotating membrane or rotating cable supported mesh, electrostatic membranes, and inflatables. Mesh deployable-antenna concepts are based on using a variety of techniques to shape their flexible surfaces into approximations of the desired apertures. Precision deployable-antenna concepts are characterized by apertures comprised of rigid, curved, segmented reflector elements that are kinematically

connected to each other and/or to a primary supporting structure. The mesh deployable structures, with their good mechanical packaging efficiency, are intended for applications requiring apertures up to several hundred meters in diameter and operating frequencies of Ku-band and above for the smaller sizes and UHF and above for the larger sizes. This class of antenna is the most mature and has flight experience with the Lockheed wrap-rib antenna on the ATS-6 Satellite, the Harris radial-rib antenna on the TDRSS, and the TRW radial-rib antenna on the FLTSATCOM. This class of antenna is well suited for application to MSAT-2. Precision deployable antennas, with their near continuous reflector surfaces, which can accommodate RF operation up to 60 GHz, are limited by their mechanical packaging efficiencies to functional diameters of 10 to 20 meters, depending on the specific concept. Because of their lower packaging efficiencies as compared to mesh antennas, this class of structure, for a given deployed diameter, would require considerably more stowed volume. Additionally, for a given diameter, precision deployable antennas weigh on the order of twice as much as mesh antennas.

Consequently, this class of antennas was not considered for MSAT-2. At this time the technology for membrane antenna concepts is too immature for their consideration for MSAT-2.

2.6.4 Antenna Descriptions

2.6.4.1 Wrap-Rib Antenna

The wrap-rib antenna reflector configuration is based on a variable number of radial ribs or beams which are cantilevered from a central hub structure. Each of the ribs is attached to the hub structure through a hinge at the root

of the cantilever. This radial spoke provides the mounting for the antenna reflector surface. For parabolic or other curved apertures, the ribs are manufactured to the required shape and reflective pie-shaped gores of membrane material, which is usually knitted or woven fabric, are attached between the ribs.

The rib cross-section and material are chosen to permit the elastic buckling of the ribs in the stowed configuration, Figure 2-10. This allows the ribs to be compactly wrapped around the hub structure. In the antenna stowing process, the ribs with the mesh gores folded between them are rotated about the rib's root hinges until the ribs are tangent to the hub. After this initial rotation, the ribs are elastically buckled and wrapped completely around the hub structure. The RF-reflective mesh gores form a package between the rib structures.

Antenna deployment is accomplished for small systems (less than 5 m in diameter) by releasing the strain energy in the stowed ribs. For antennas of this size, the stowed package is contained by a series of hinged doors, held in place by a restraining cable. Deployment occurs when the cable is severed. For antennas 10 meters and larger, where the deployment reaction is large, the deployment restraint system uses a tape and pully system. With this system, a tape is placed between the second or third rib, such that the tape under tension keeps each rib loaded around the hub, Figure 2-10. For deployment, a motor drives a gear, which in turn rotates the tape take-up reels. The ribs deploy as the tape is reeled up. A constantly slipping clutch is located in each tape reel drive to limit the tape tension and allow positional and speed variations from rib to rib during deployment.

The feed support structure, for the offset antenna configuration, is a deployable boom that originates at the reflector hub structure, Figure 2-11. (See Chapter

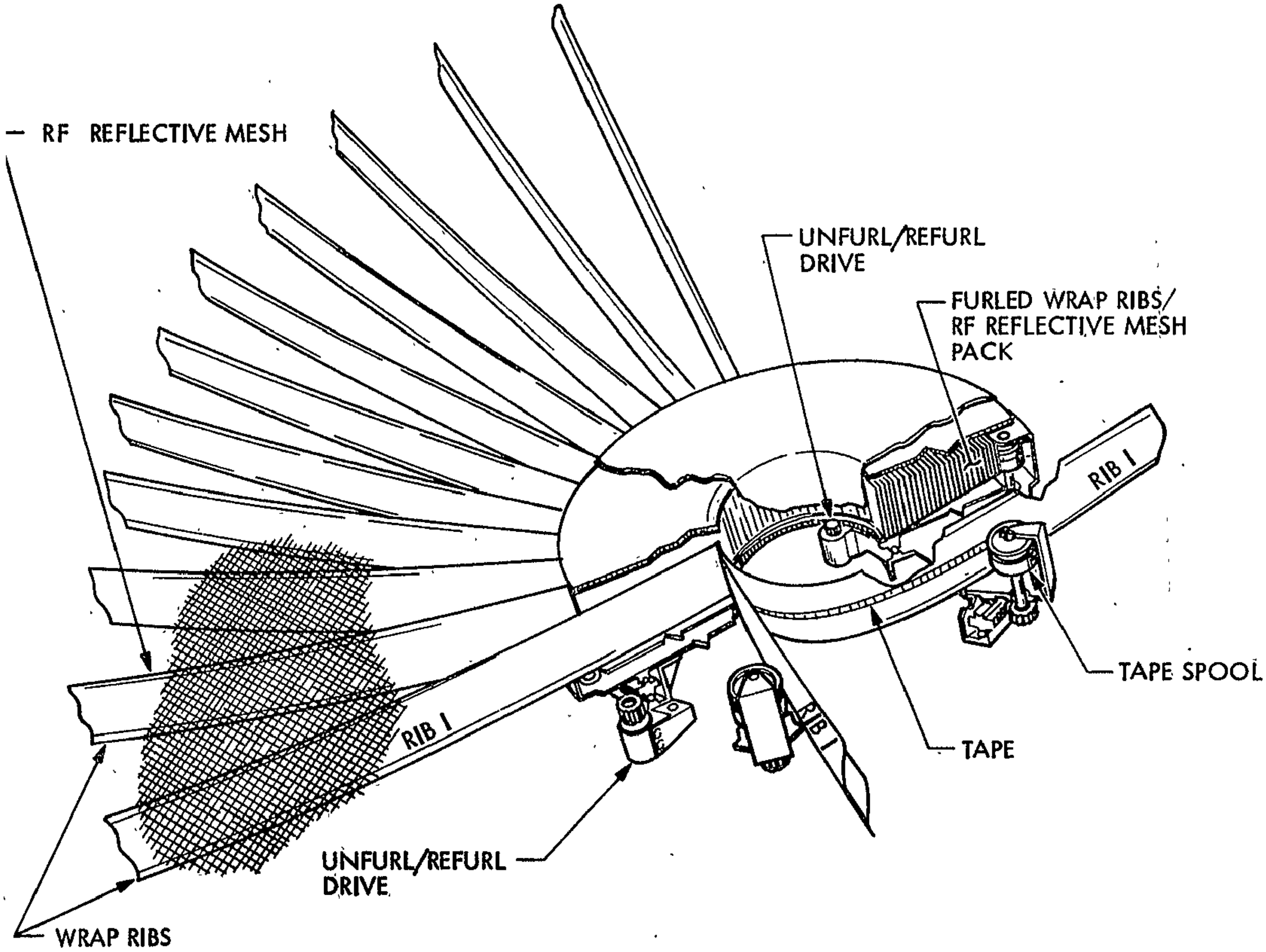


Figure 2-10. Wrap-Rib Antenna Deployment Scheme

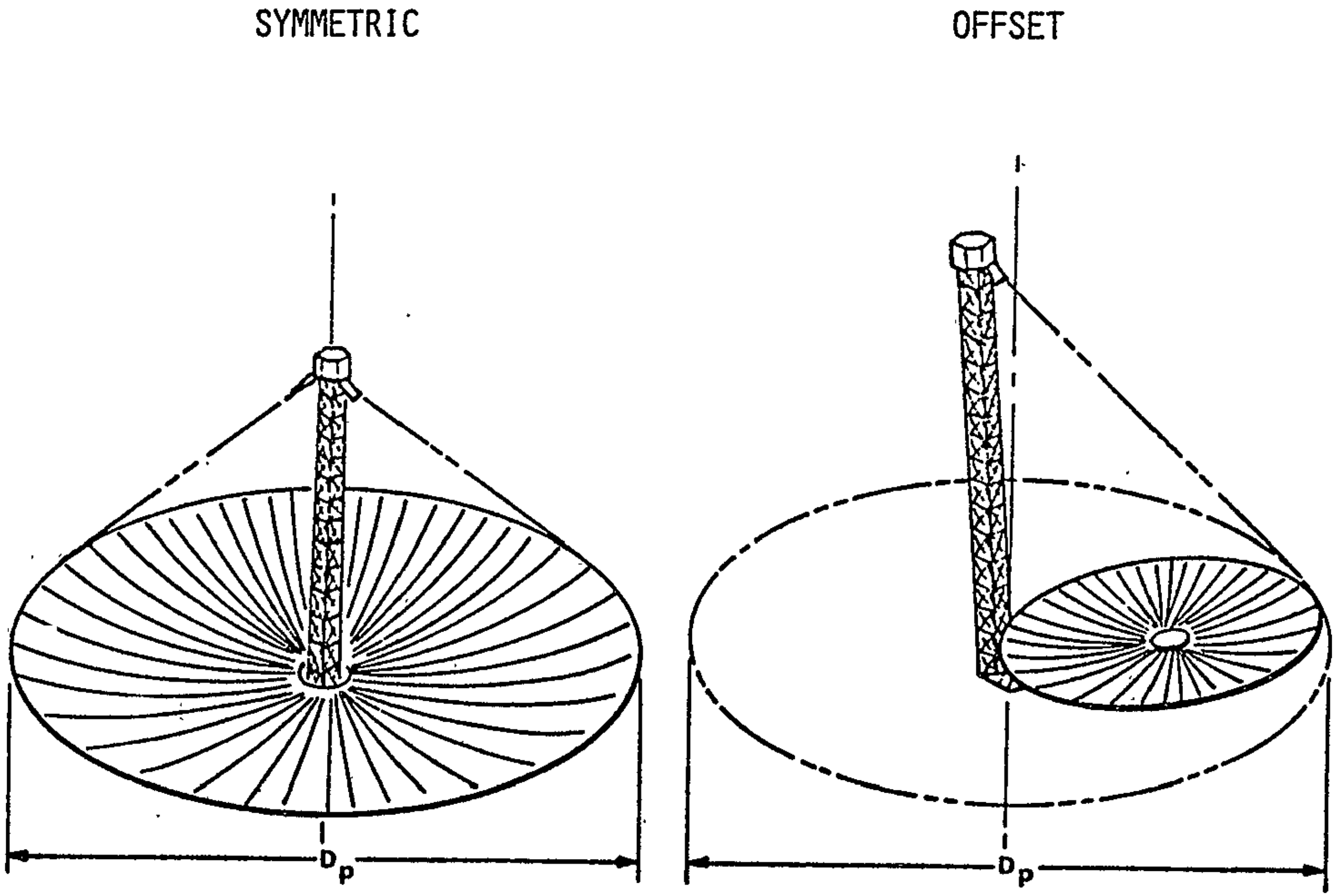


Figure 2-11. Wrap-Rib Reflector Geometry

3 for the possible MSAT-2 configurations.) It is a cantilever which extends radially past the deployed ribs before making a 90° direction change so that its longest leg is colinear with the antenna axis and terminates at the focus of the reflector. A baseline design for this configuration was developed for large structures, i.e., 50 meters and larger. This baseline is a tetrahedral truss-type boom that utilizes tapered, folding longerons and tensioned diagonals, Figure 2-12. However, this design is probably not optimum in terms of weight and mechanical packaging efficiency for smaller antennas. Therefore, a modification of this baseline or the application of other boom configurations is required to optimize this structure for MSAT-2.

2.6.4.2 Hoop/Column Antenna

The major elements of the maypole support structure (hoop/column) concept include the hoop, upper, lower, and center control stringers; and the telescoping mast, Figure 2-13. The reflector aperture consists of the mesh, mesh-shaping ties, secondary drawing surface, and the mesh-tensioning stringers. The basic antenna configuration is a type of maypole with a unique technique for contouring the RF-reflective mesh surface, Figure 2-14.

The hoop's function is to provide a rigid, accurately located structure to which the RF-reflective surface can attach. It is comprised of rigid sections which articulate at hinges joining adjacent segments. These segments consist of two tubular, graphite-fiber members, parallel to each other, and attached to a long hinge member at each end. Torsion springs and actuators located in the hinge supply the total energy required to deploy the hoop.

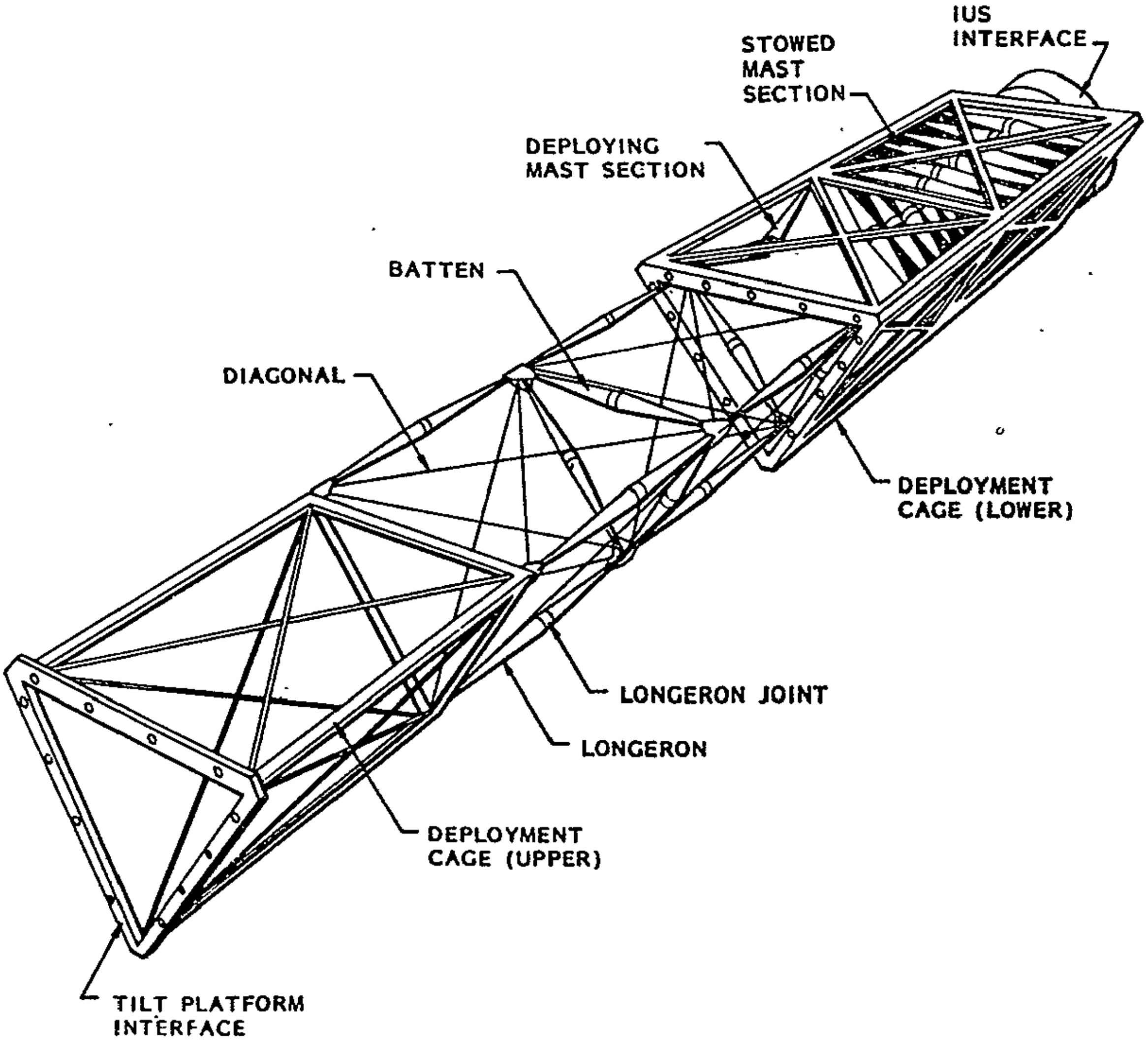


Figure 2-12. Wrap-Rib Antenna Feed Support Structure

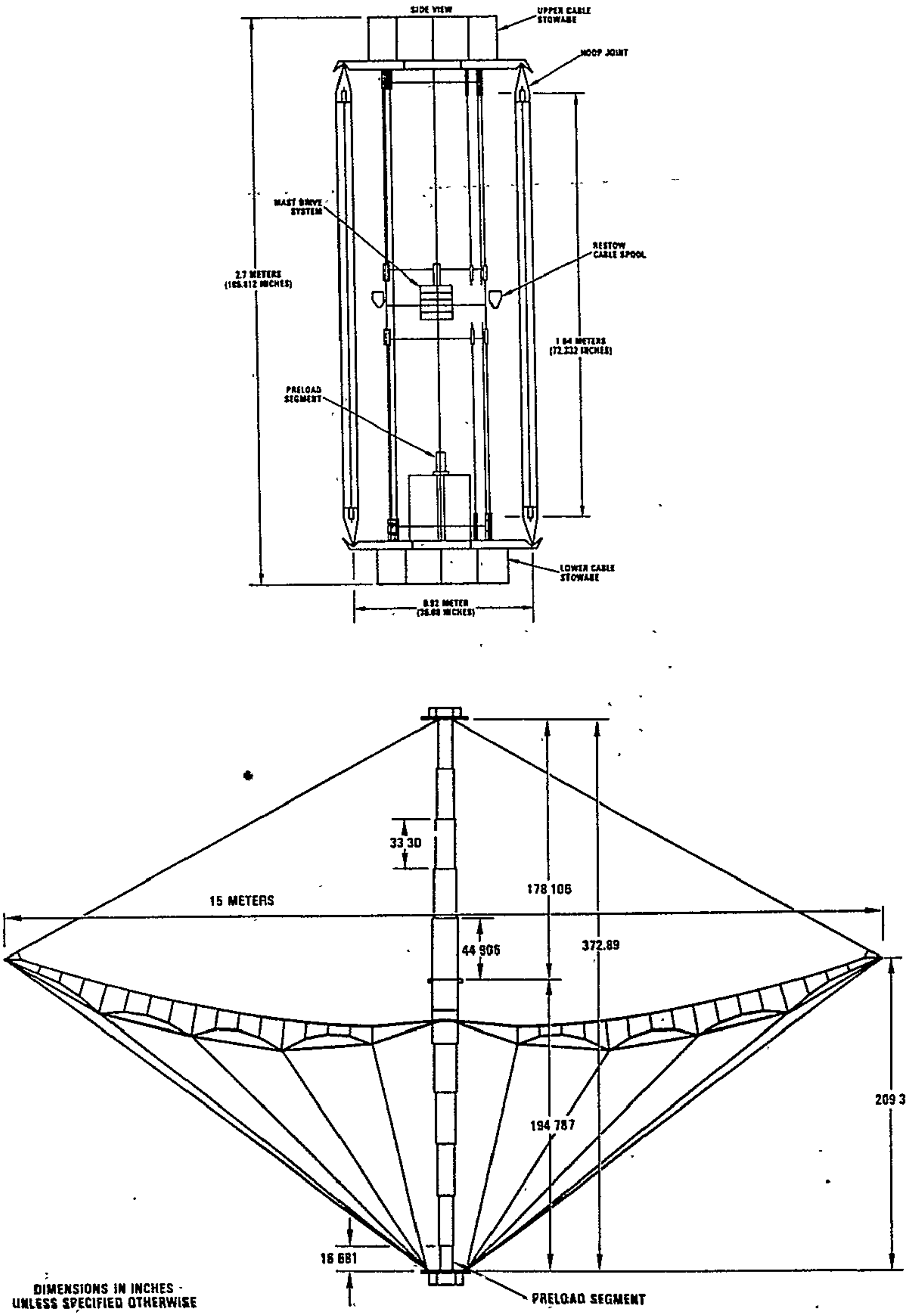


Figure 2-13. Hoop/Column Antenna Geometry (15-m Model)

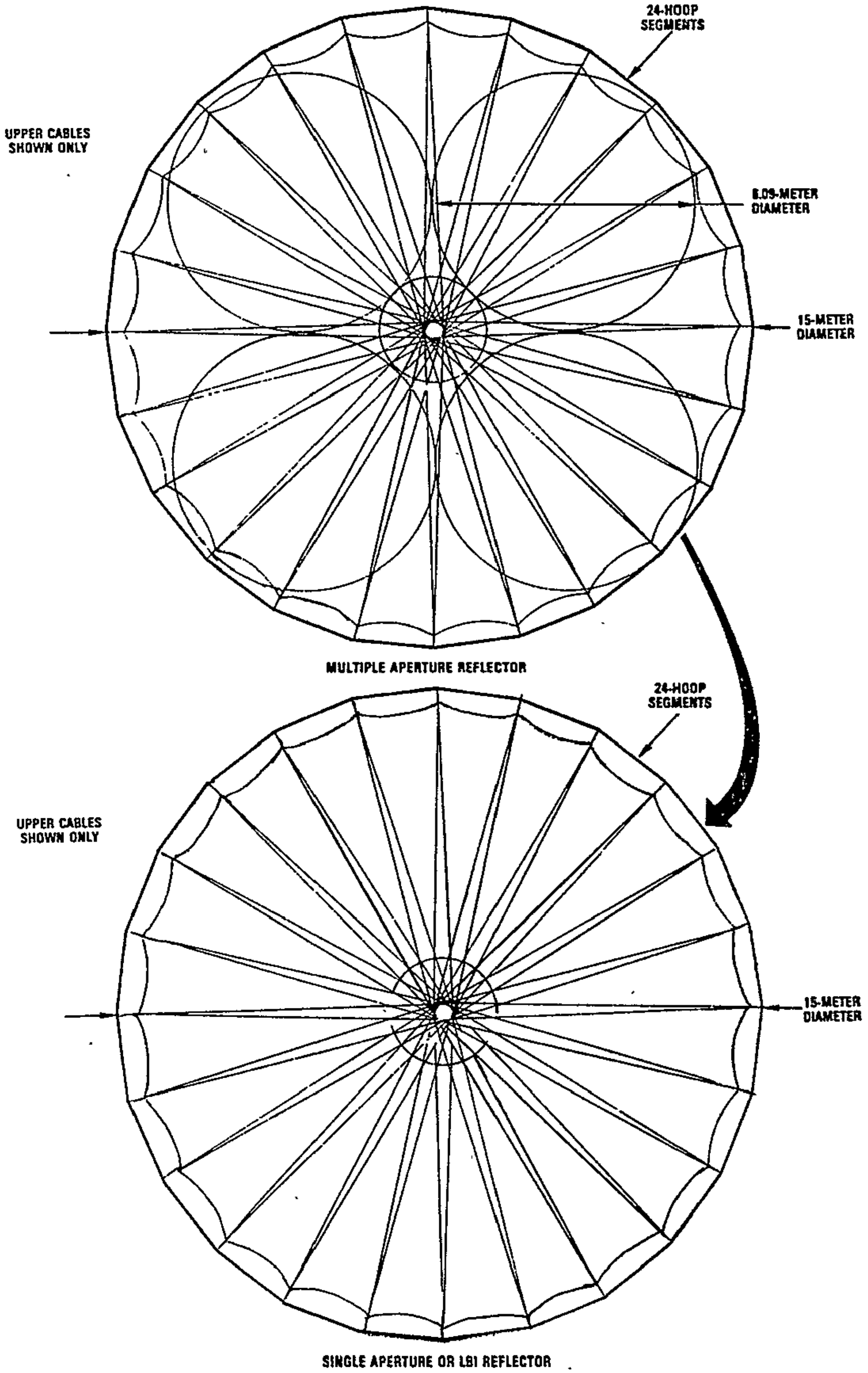


Figure 2-14. Hoop/Column Antenna Configuration (15-m Model)

The central column, or mast, is deployable and contains the microwave components and control mechanisms. It consists of tubular graphite/epoxy members that, for a series of cages, nest inside each other when stowed. Aside from housing various components, the mast provides attachment locations for the reflective surface and the stringers.

Five sets of stringers are used on the maypole (hoop/column) concept. Three of these sets are used for hoop deployment and control, while the other two sets are used for mesh shaping. The hoop-control stringers are located at the upper end, the center, and the lower end of the mast; they extend radially outward to their attachment positions at the hinges of the hoop. The upper and lower control stringers accurately position the hoop throughout its deployment, relative to the mast. The center control stringers are used for rate control during deployment and for moving the hoop joints toward the mast, against their spring forces, during the automated antenna stowing sequence. The remaining two sets of stringers (mesh-tensioning stringers) are located just above the lower control stringers and are used to shape the reflective surface into the proper contour. All of these stringers are made of quartz cords for high stiffness and thermal stability.

The mechanism that permits shaping of the gold-plated molybdenum wire mesh consists of numerous radial quartz stringers, to which the mesh is directly attached (mesh surface stringers), along with a similar set of stringers (secondary drawing surface stringers) positioned beneath them. Short ties (mesh-shaping ties), made of fine wire, connect the RF mesh surface stringers to the secondary drawing surface stringers. When the mesh-tensioning stringers are positioned, they in turn apply tension to both the secondary drawing surface stringers and the mesh-shaping ties to produce an essentially uniform presure distribution on the mesh which results in an approximation of the desired curvature.

2.6.5 Antenna Concept Evaluation Criteria

The potential value of any antenna concept is a function of how well it satisfies the requirements for a specific application. There are a number of factors that must be considered when determining a concept's value, including deployment reliability, surface precision, feed alignment, hardware cost, mechanical packaging efficiency, weight, long-term dimensional stability, and applicability to ground evaluation. One of the most important aspects of this class of structures is the reliability associated with the mechanical deployment of the antenna. The confidence associated with the deployment of a specific antenna structure is proportional to the complexity of the structure and the maturity of the concept.

The RF performance is dependent on the on-orbit reflector precision and reflectivity and the alignment of the feed support structure relative to the best-fit aperture. Estimates can be made for these tolerances based on the results of analytical models and ground tests. However, flight experience will be required to characterize these tolerances and validate the analytical models well enough to accurately predict on-orbit RF performance.

The flight hardware cost is important, especially for large structures, because it can be the determining factor as to whether specific applications are affordable since the antenna can represent the greatest subsystem expenditure.

The mechanical packaging efficiency, i.e., the ratio of stowed-to-deployed diameter, establishes the maximum functional size of the structure that can be accommodated by the STS payload compartment. This characteristic varies considerably among the different antenna concepts.

Antenna subsystem weight is another very important consideration for applications utilizing large structures in high orbit, since the antenna weight fraction is a significant contributor to the requirements for upperstage boost capability.

The majority of the antenna concepts are based on graphite epoxy construction, which is subject to dimensional changes as a consequence of exposure to the space environment. Therefore, the potential performance reduction for very long-term missions must be considered when evaluating specific concepts.

Some antenna applications are based on a series of missions that start with proven and high-confidence technology that advances with each successive flight system. Frequently, this approach dictates the need for successfully larger, and possibly higher, performance antennas. For this class of applications, the antenna-concept growth potential is extremely important.

The dynamic characteristics of large antenna structures in the orbital configuration have a major impact on the type of control system needed to accommodate mission requirements. These characteristics, for equivalent size structures, vary significantly as a consequence of the differences in structural configuration.

Thermal distortion is one of the major sources of reflector surface and feed support structure, mechanical-alignment errors. Consequently, these effects must be carefully considered when estimating antenna orbital performance.

Ground-based test limitations represent one of the most significant problems associated with developing and evaluating concepts for large, deployable structures. The test fixturing required to accommodate the demonstration of antenna deployment, structural alignment, and aperture precision can complicate and/or mask the true structure performance to the point of limited cost effectiveness. The applicabilit

to ground testing for specific structures is a function of their configuration, kinematic complexity, and relative structural stiffness.

2.6.6 Baseline Deployable Antenna

The two mesh deployable-antenna concepts were evaluated using the results of the respective study contracts. From a technical point of view, either concept has the potential for meeting the requirements of MSAT-2 and is considered acceptable. Since a single-baseline system configuration was developed by the MSAT-2 study, one antenna concept was selected as the baseline.

The wrap-rib antenna concept was selected as the baseline for MSAT-2. However, this does not preclude the consideration of any other antenna concept for subsequent MSAT-2 studies, technology developments, or applications. The wrap-rib reflector was selected on the basis of its demonstrated concept maturity. Such demonstrations included the successful ATS-6 satellite (Figure 2-15), Lockheed's functional 15 - (Figure 2-16) and 44-meter diameter reflector models, and the Large Space System Technology (LSST) proof-of-concept, 55-meter model (Figure 2-17). Even though the wrap-rib reflector concept was selected for the baseline, no specific concept for the offset deployable-feed support structure was selected as a baseline. There are a number of concepts for deployable booms that have the potential for application with the offset wrap-rib reflector structure. Another phase of antenna concept evaluation is required to accommodate the selection of a deployable-feed support structure whose mechanical performance is complementary to the existing wrap-rib reflector maturity.

ORIGINAL PAGE IS
OF POOR QUALITY

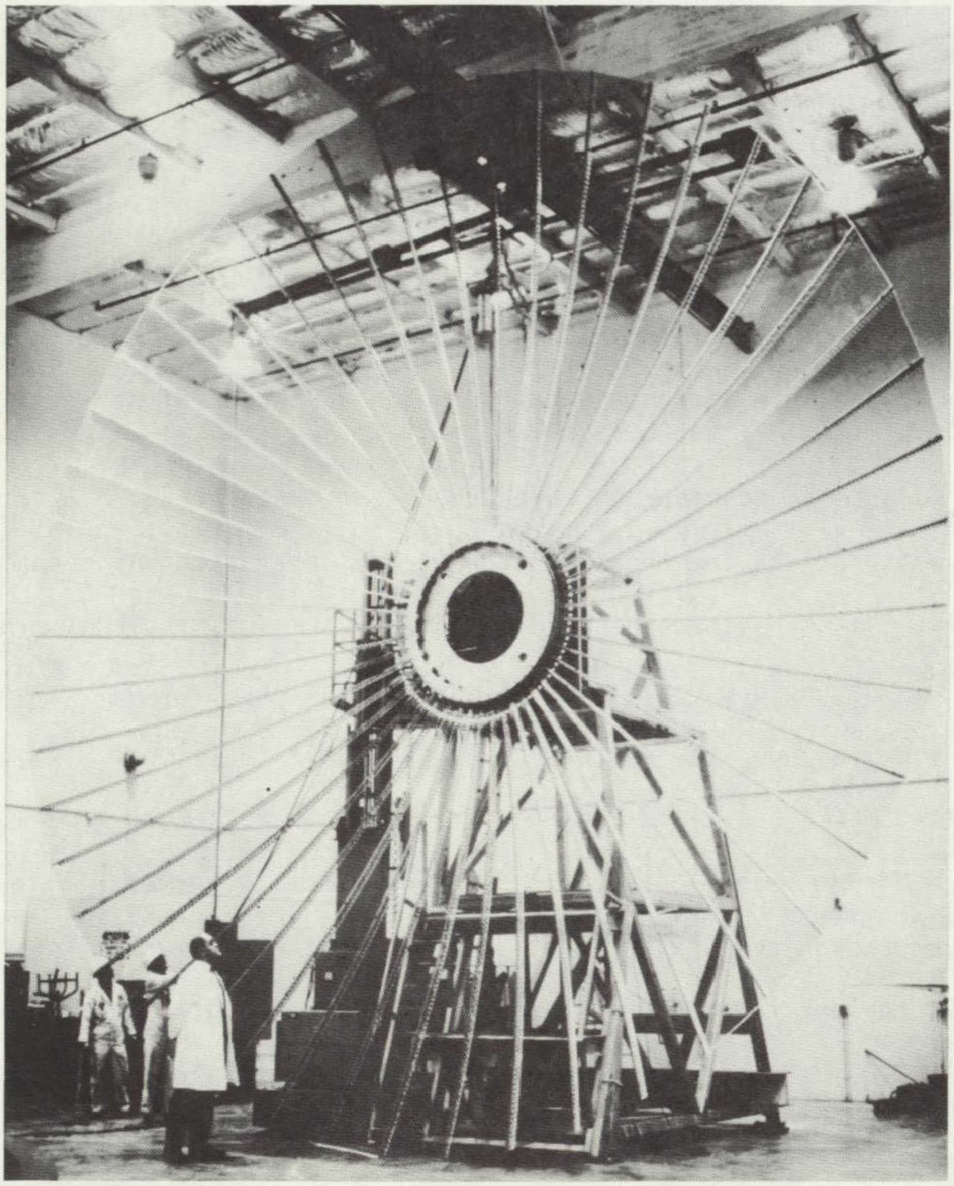


Figure 2-15. Wrap-Rib 9-m ATS-6 Antenna

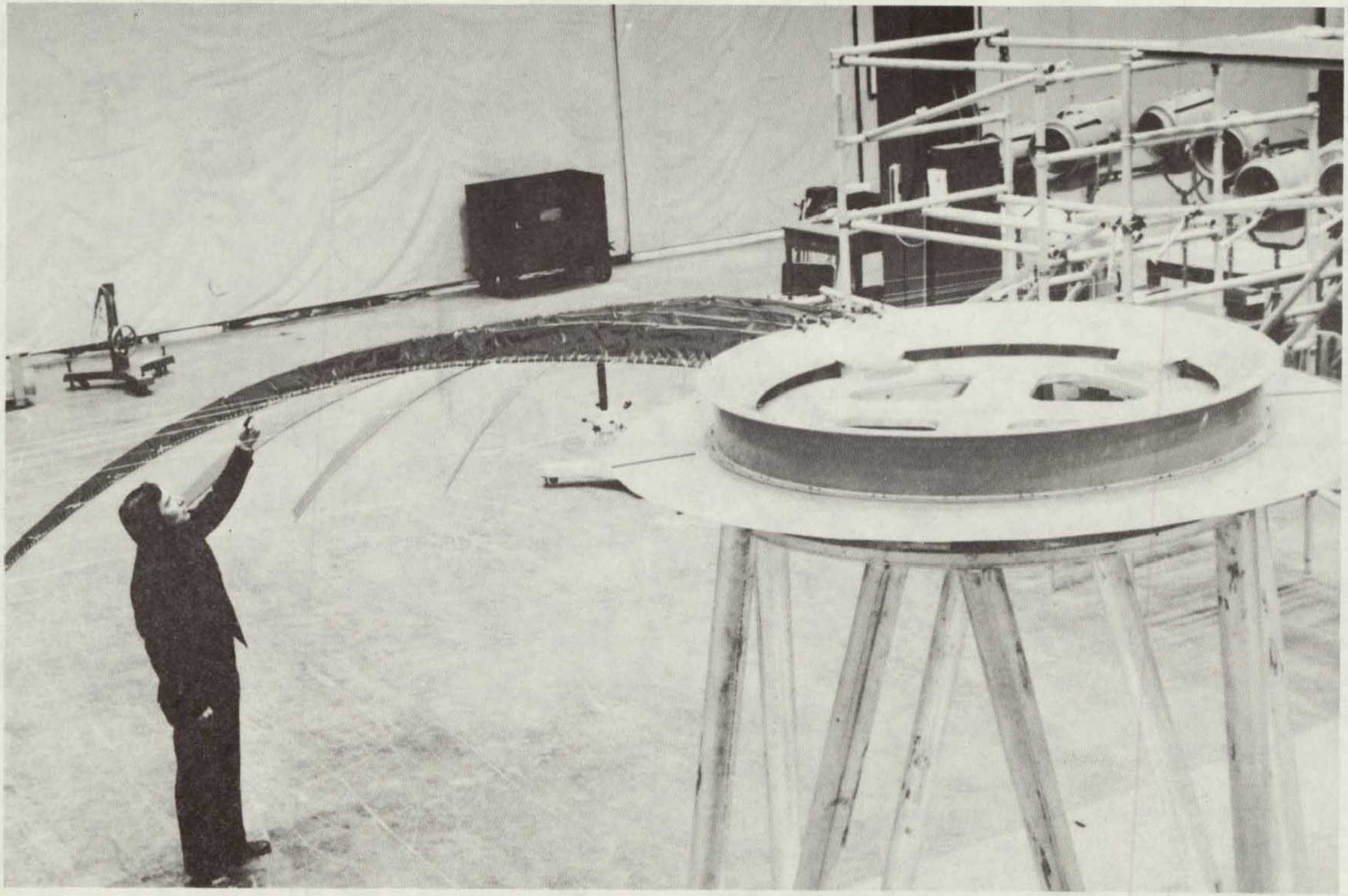


Figure 2-16. Wrap-Rib Antenna, 15-m Model

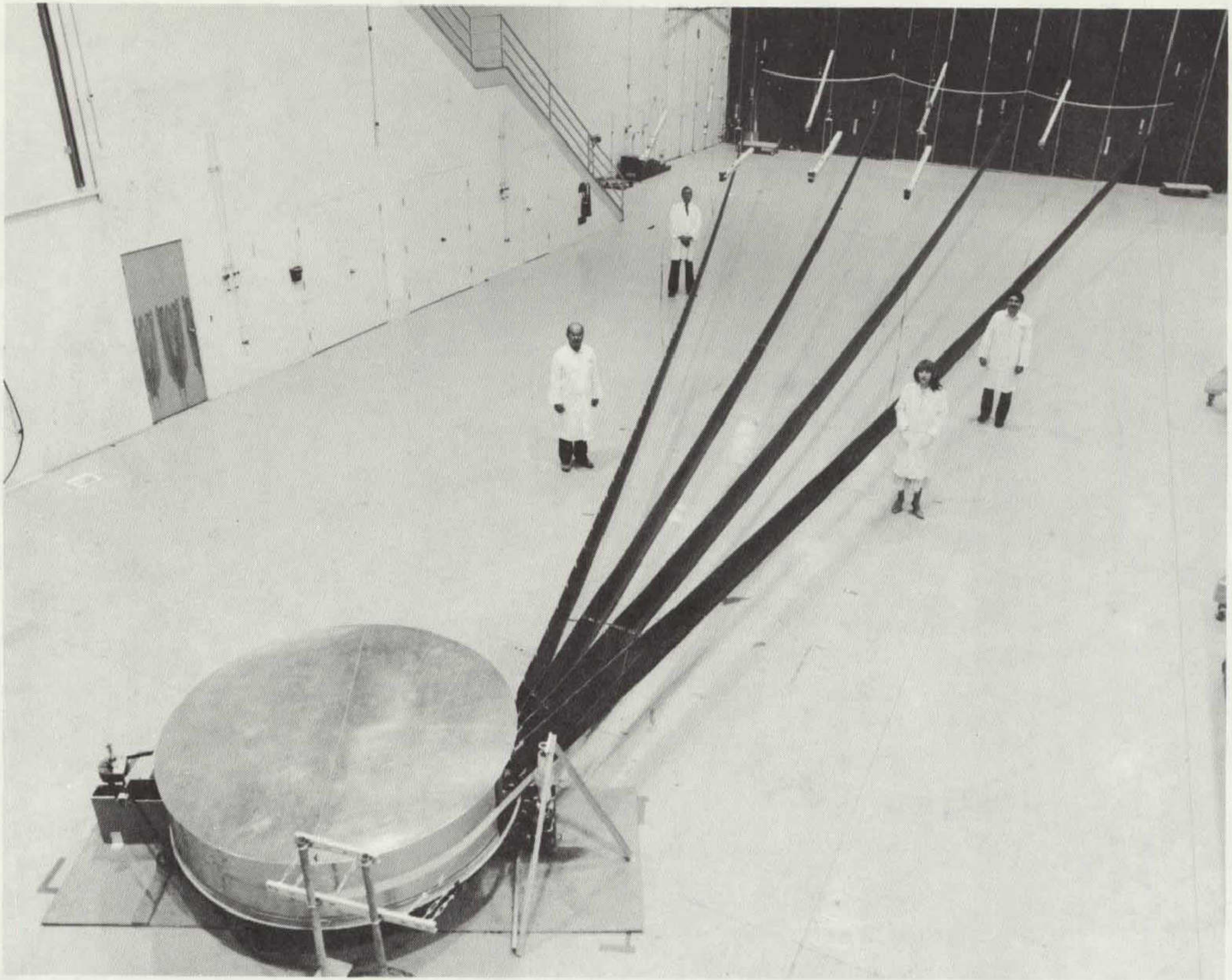


Figure 2-17. Wrap-Rib 55-m Proof-of-Concept Model

can be shown that of all the circular aperture antennas illuminating a circular region, the one with 4.34-dB fall-off at the edge of coverage from the center produces the highest gain at that point. Secondly, it is very easy to observe that the full coverage of a given region with a uniform two-dimensional grid of beams, with a minimum overlap of adjacent beams, is achieved with an equilateral triangular grid configuration. Based on the above two considerations, the optimum full coverage of a given region with multiple circular beams is achieved with overlapping beams as shown in Figure 2-18. In this arrangement adjacent beams touch at the 3.25-dB level and intersect at the 4.34-dB level. The amount of overlap between adjacent beams is only 5.77 percent of each beam (as opposed to, e.g., 18.17 percent for a similarly arranged rectangular grid). For reasons of simplicity and conformity with convention, we choose the crossover at the 4-dB level (instead of 4.34) and contiguity at the 3-dB level (instead of 3.25). The loss of gain in this modification is negligible while the required reflector diameter is also slightly smaller. From this point on whenever reference is made to the beamwidth or beam footprint size, unless otherwise indicated, the half-power or 3-dB contiguous footprint is meant.

By projecting the boundary of coverage area into the satellite antenna coordinate system and superimposing the grid of beams, the configuration and number of required beams are obtained. Once the number of beams is fixed the frequency reuse scheme can be decided on the basis of a trade-off between required satellite power and the desirable number of channels on the one hand, and the acceptable C/I (carrier-to-interference) ratio, on the other. If the reflector diameter is not given a priori, then again by a trade-off of the required power and total channel capacity, the number of beams, the beamwidth, and the frequency reuse factor can be selected such that an acceptable C/I is maintained.

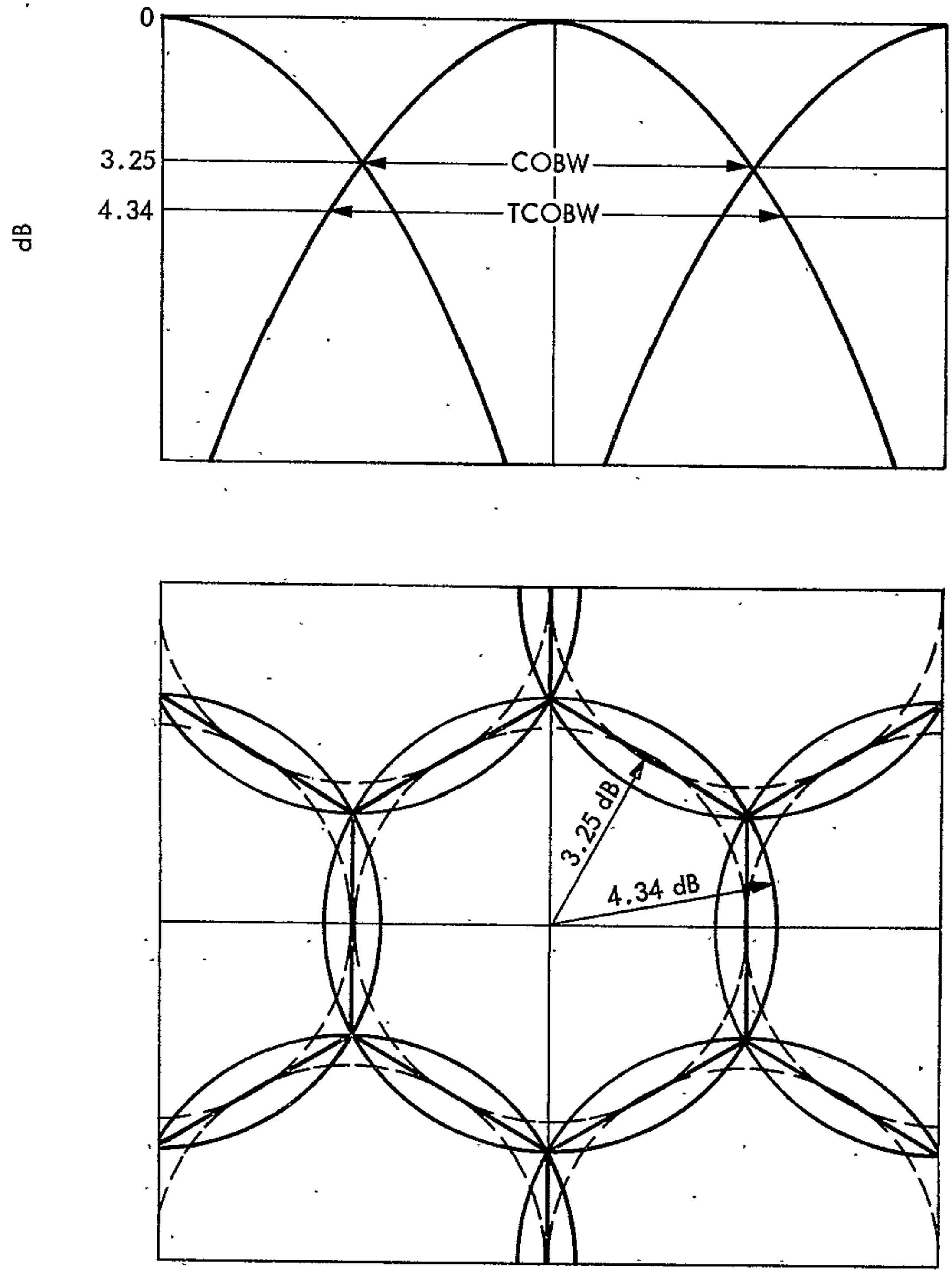


Figure 2-18. "Optimum" Configuration and Interbeam Separation in a Full Coverage Multibeam System

2.7.2 Feed Elements and Feed Array Configuration

Based on the selected geometry of the antenna and the multibeam feedprint layout on the coverage region, the geometrical configuration of the radiating elements (which illuminate the reflector and produce the beams), i.e., their location on the local surface and interfeed separation, can be obtained. Theoretically, all the feed elements should be located on the nonplanar "focal surface." But due to practical structural considerations, the feeds will be laid out on the offset focal plane, i.e., the plane passing through the focal point and perpendicular to the line joining this point to the "center" point of the reflector aperture as seen in Figure 2-9. Furthermore, for ease of implementation, the elements will be laid out in a uniformly spaced, equilateral triangular grid similar to the multibeam layout. Once the feed array is laid out in such a fashion, the resulting layout of the beams over the coverage region will somewhat deviate from a uniform grid configuration due to the beam deviation factor. For proper illumination of the reflector all the feed elements should be directed toward the center of the reflector [8]. For off-focus feeds this may be accomplished by the proper phasing of the subelements comprising the feed. In a single-subelement feed, however, this is not possible. In that case either the loss should be accepted or the element mechanically tilted toward the center.

The interfeed separation is dictated by the interbeam separation and the F/D of the reflector. Thus, the separation between the centers of any two adjacent feeds, s, is approximately given as

$$s/WL = (1.135/b)\ (F/D)\ \ (COL/3)^{1/2} \qquad (2\text{-}2)$$

in which WL is the wavelength, b is the beam deviation factor (less than but close to unity), and COL is the contiguous crossover level of adjacent beams whose near

optimum level, as mentioned in 2.7.1, is 3 dB. Thus, it is interesting to note that the interfeed separation in terms of wavelength is approximately equal to the F/D ratio. This separation is also the diameter of the circular region available to individual feeds. The required area per feed and the feed composition, however, are functions of the desired far-field beam pattern characteristics. Thus, the feed size and configuration should be selected so as to optimize the gain and/or sidelobe characteristics. These are dependent on the feed illumination function at the reflector. The primary factor is the illumination taper at the edge of the reflector, FET, as shown in Figure 2-19. In general, increasing the edge taper requires a larger feed diameter, d, which is approximately given by

$$d/WL = 1.135\ (F/D)\quad (FET/3)^{1/2} \qquad (2\text{-}3)$$

For gain optimization, a feed edge taper of approximately 10 dB is required which from Eq. (2-3) leads to a desired feed diameter twice F/D in terms of the wavelength. Thus, a conflict between the required feed size and the available feed area is created. If very low sidelobes are required, so that the interbeam isolation in a frequency reuse scheme is kept below a certain level, then even higher values of the feed edge taper and consequently larger feed diameters might be needed. It should be emphasized that not only the edge taper, but the entire shape of the illumination function could affect the gain and sidelobe characteristics. Specifically, the slope of the illumination function at the edge, has a significant effect on sidelobe characteristics. Sidelobe levels decrease as the slope decreases for a given edge taper. This is especially important in multi-element feeds in which by proper design of the elements, their spacing and excitation levels, the total feed pattern can be tailored to produce both the desired edge taper and edge slope. In single-element feeds, the edge taper and slope are usually not independent and once a particular edge taper is selected the edge slope cannot be arbitrarily specified.

BEAM SEPARATION DICTATES FEED SEPARATION

$s/WL = (F/D)\sqrt{COL/3}$

* CONFLICT *

GAIN OPTIMIZATION AND/OR SIDELOBE LEVELS DICTATE FEED SIZE AND CONFIGURATION

$d/WL = (F/D)\sqrt{FET/3}$

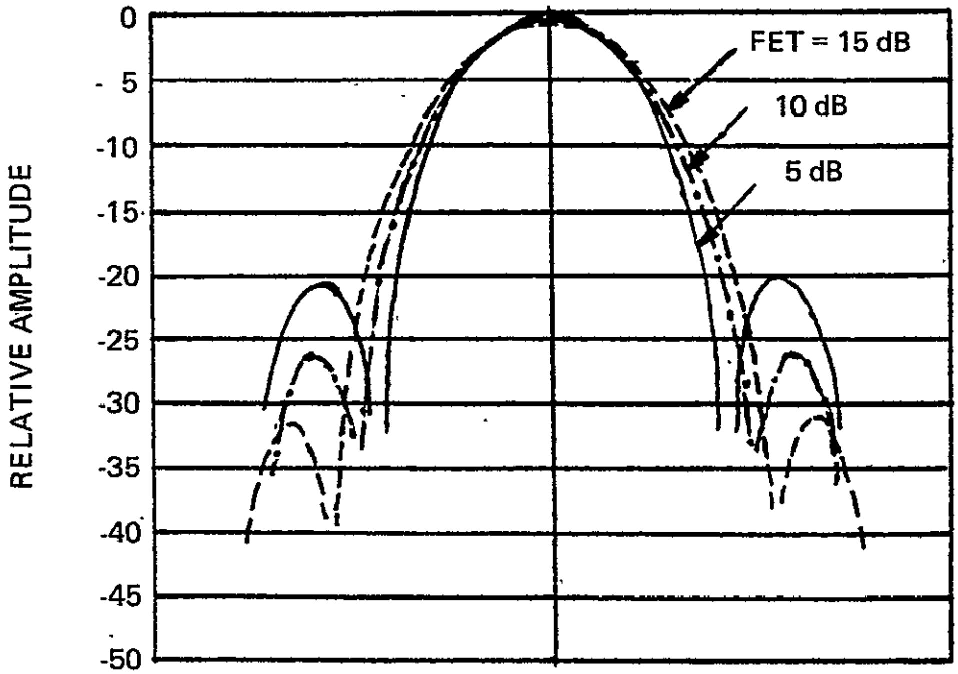
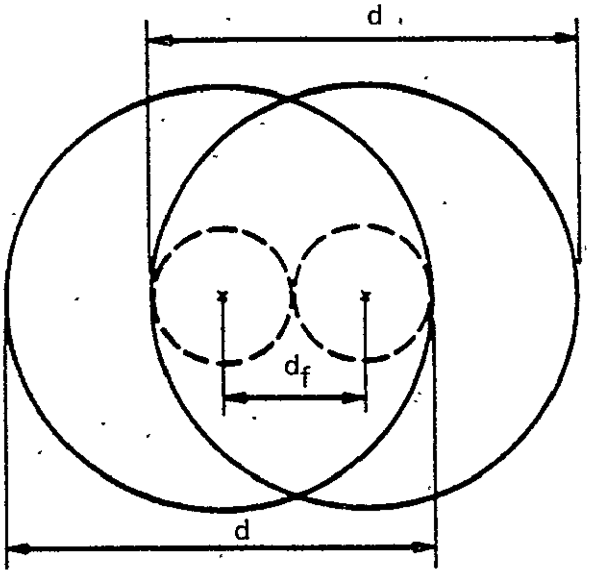


Figure 2-19. RF Performance vs. Feed Size and Configuration

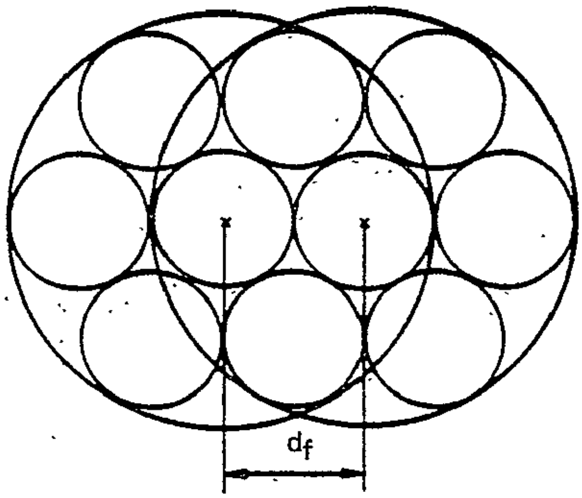
At any rate, in most cases of interest the required feed area exceeds the available real estate. A solution to this problem can be provided by an overlapping cluster feed arrangement as demonstrated in Fig. 2-20. In this arrangement a few elements are shared among adjacent beams, thus providing a larger overall feed area per beam. For example, in Fig. 2-20, each beam uses seven elements while each element is also shared, in general, by seven beams. This technique, however, requires an elaborate beam-forming network, an increase in the overall feed array size, etc. A detailed account of such a system is given in [6], [9], and [10].

Some possible overlapping cluster feed arrangements are shown in Fig. 2-21. Notice that in this arrangement each element itself can be composed of one, two, four, or more subelements. In Fig. 2-21, one subelement shown is a square microstrip patch, although many other feed element types are possible. In a cluster feed arrangement the separation between elements (usually from half to equal the interfeed separation, s, as given in Eq. (2-2)) is decisive in determining whether or not the overall feed pattern has high grating lobes. These lobes fall beyond the reflector edge and cause generally high levels of gain loss (1 to 2 dB) in addition to creating other problems (such as specious lobes in a multi-aperture reflector [11]). For this reason the interfeed separation, s, in terms of the wavelength, which is almost equal to F/D, should be kept below 0.5 for eliminating grating lobes or below unity for acceptable levels of these unwanted lobes. However this might not be possible in cases with a very large number of beams in which F/D must be chosen larger than unity in order to maintain the integrity of the scanned beams.

Finally, once the size and configuration of the cluster feed is decided, optimization routines must be employed in order to select the appropriate excitation levels in different elements. There are two general methods for doing this. In one method the element phase and amplitude are optimized so that a desired distribution in the aperture plane (plane phase and desired amplitude taper) is obtained. In a second and more direct method, the problem is formulated directly in terms of a set of



a) Two Overlapping Single Feeds (Physically Impossible)
(The Dashed Circles Represent the Largest Physically Acceptable Single Aperture Sizes)



b) Two Overlapping 7-Element Cluster Feeds (Four Common Elements)

Figure 2-20. Overlapping Cluster Feed Concept

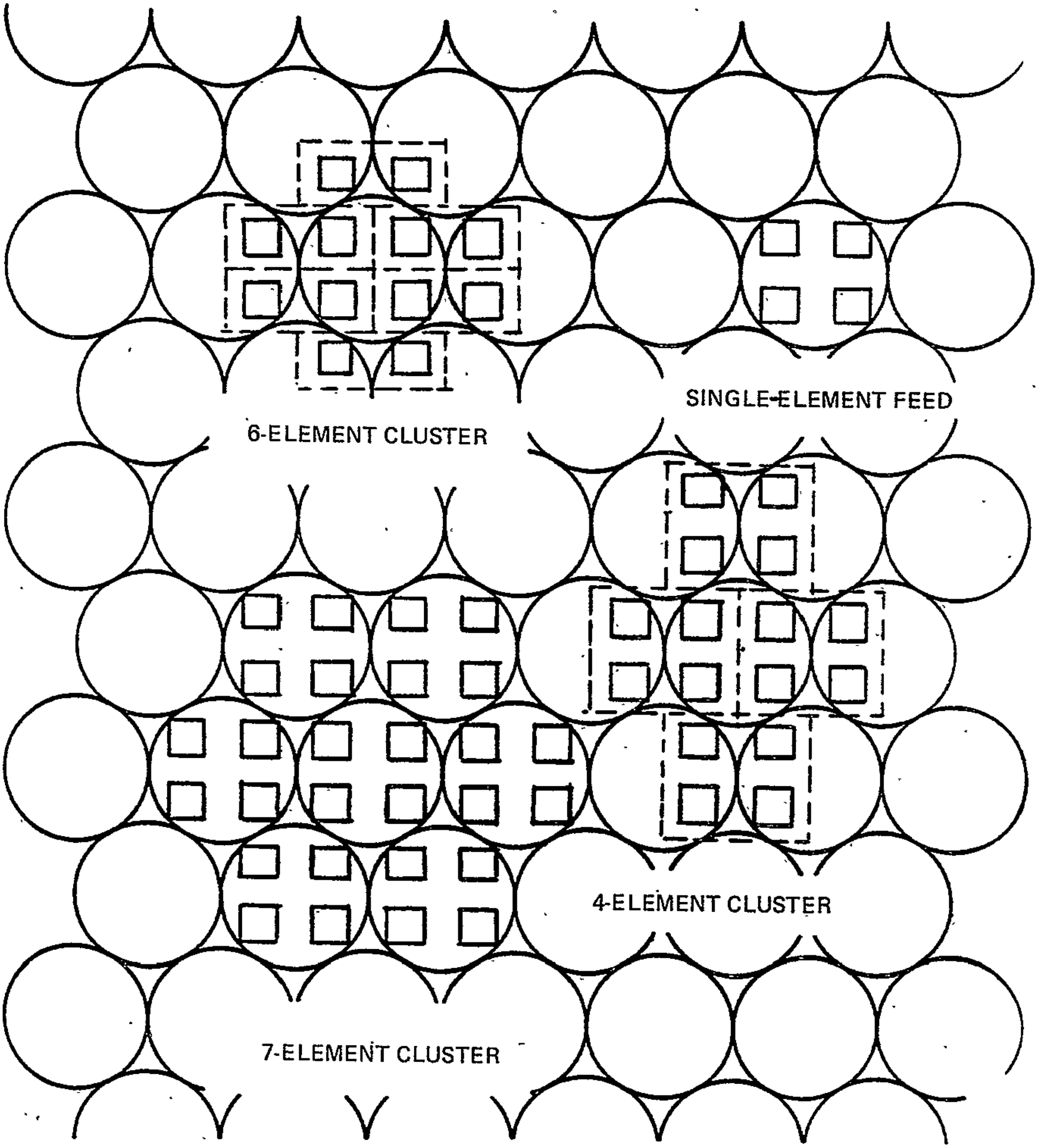


Figure 2-21. Some Feed Cluster Arrangements

constraints on the main beam and sidelobe levels in the farfield pattern. Then, by varying the cluster amplitude and phase, those objectives are achieved.

As far as the selection of radiating subelements are concerned there are a variety of elements available and suitable for various applications, such as

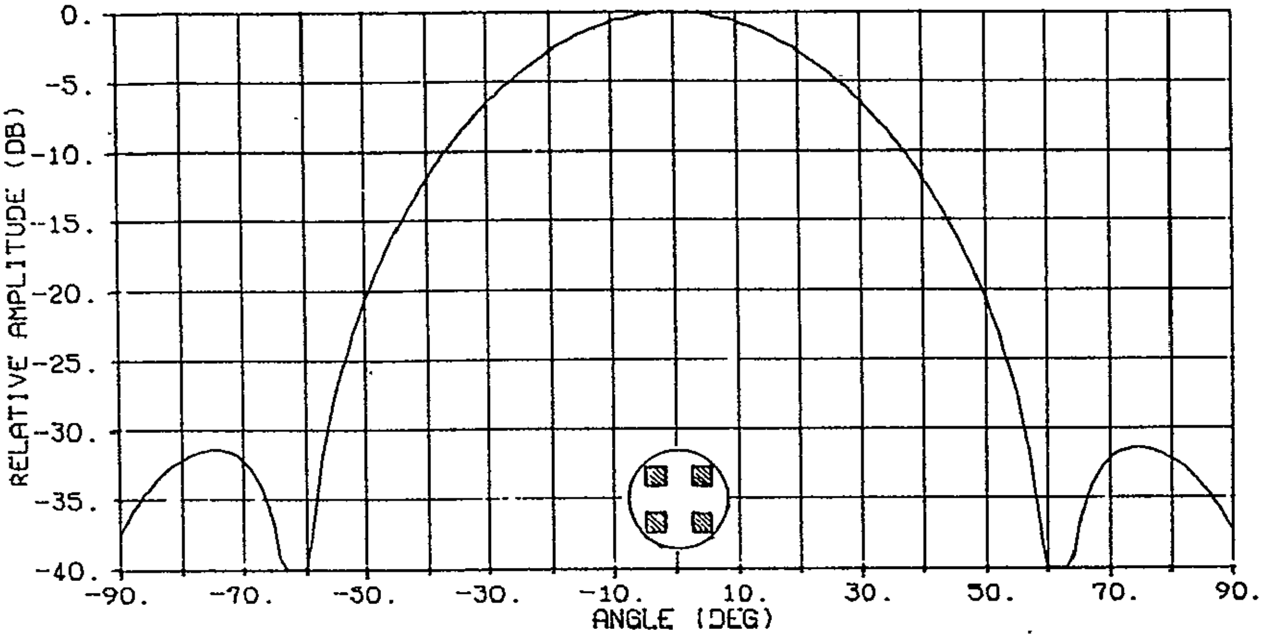
- waveguide aperture
- simple and corrugated horns
- backfire elements
- cigar antennas
- multifilar spiral antennas
- microstrip patch antennas.

The most appealing choice, perhaps, is the microstrip patch antenna, which is mechanically and structurally simple and lends itself quite naturally to a large flat panel array configuration. It is lightweight and can be easily implemented. In most cases a honeycomb substrate can be used which is extremely lightweight and has minimal dielectric losses. The thickness of the substrate can be easily calculated to accommodate the less than 7% bandwidth for operation at both uplink and downlink frequencies. In this study the square microstrip patch is chosen as the baseline element although other shapes, such as circular, can also be gainfully employed. Circular polarization can be achieved in a variety of ways. It can be obtained by two-point feeding through microstrip lines on the array surface or with two coaxial probes from underneath to reduce cross polarization. A simpler single probe per patch might be possible if each feed or each element of a cluster feed is composed of four microstrip patches. This concept is presently under study at JPL [12].

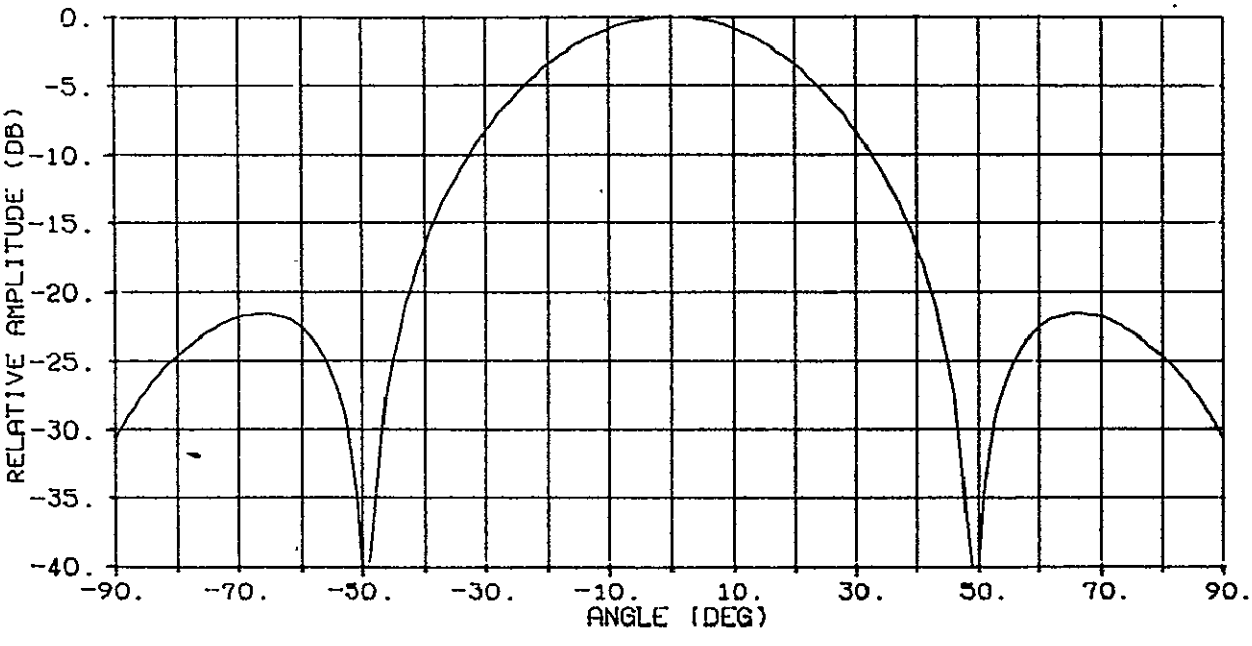
Using a square microstrip patch as a subelement in the feed cluster, a variety of clusters (Fig. 2-21) were studied. Figures 2-22 through 2-25 show typical patterns of a single element, and the clusters of four elements, seven elements (of four patches per element), and six elements (of two patches per element), respectively. Only copolarized components of the field have been shown. The corresponding far-field patterns for a 15-meter reflector at f = 845.5 MHz whose parameters are given in Fig. 2-26, are presented in Figs. 2-27 through 2-30. (All the far-field computations in this report are made with a highly efficient and accurate reflector scattering program recently developed at JPL [13].) From the presented figures the following observations can be made:

1) The efficiency of the single-element (of four patches) antenna is higher than the multi-element feeds considered. This is because the single-element feed has relatively high spillover loss (with an edge taper much smaller than 10 dB) while the multi-element feeds underilluminate the reflector as well as causing high spillovers due to the grating lobes. It is also interesting to note that among the multi-element feeds, the one with six elements (of two patches) has the best performance.

2) The very low sidelobes of the multi-element feeds are accompanied by a substantial beam broadening. This could have positive and negative effects. On the positive side, if the separation between adjacent beams is maintained at the nominal level (for example, that corresponding to the 3-dB level of the single-element feed), then an increase of perhaps 1 to 1.5 dB in gain at the edge of the beams for multi-element feeds can be achieved, which more than compensates for the gain loss at the center. Of course if the beams in a multi-element feed case are moved further apart so that they touch again at the 3-dB level, then this advantage is lost.

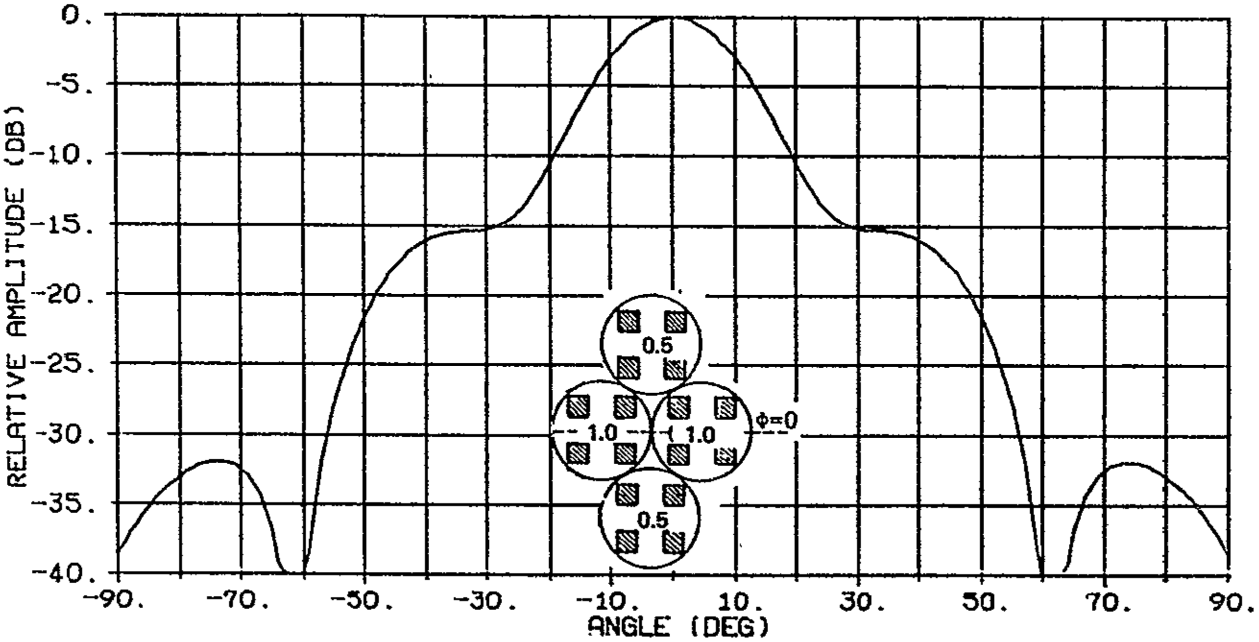


(a) $\phi = 0^{0}$ CUT

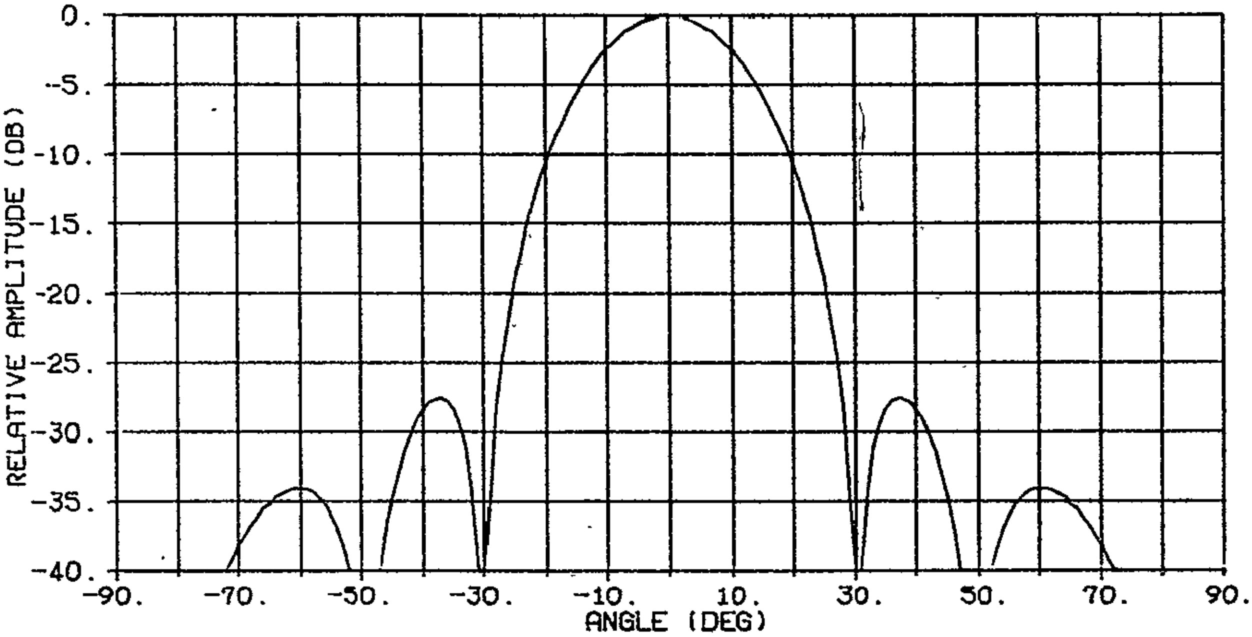


(b) $\phi = 90^{0}$ CUT

Figure 2-22. One-Element (4 Patches) Feed Pattern

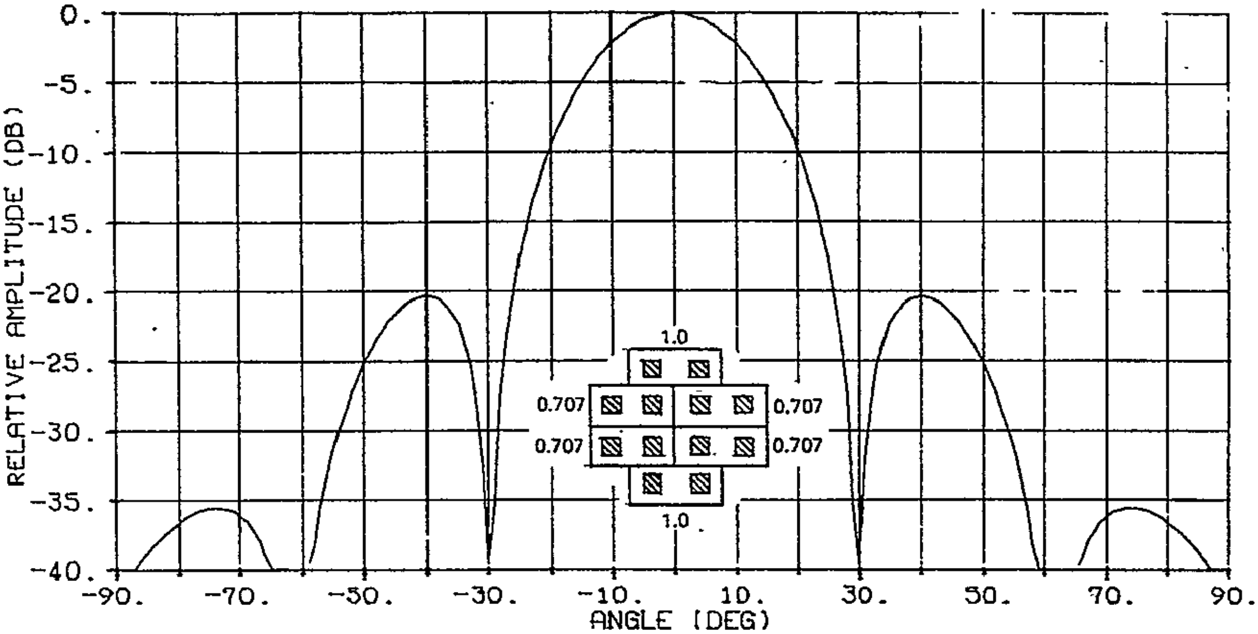


(a) $\phi = 0^{o}$ CUT

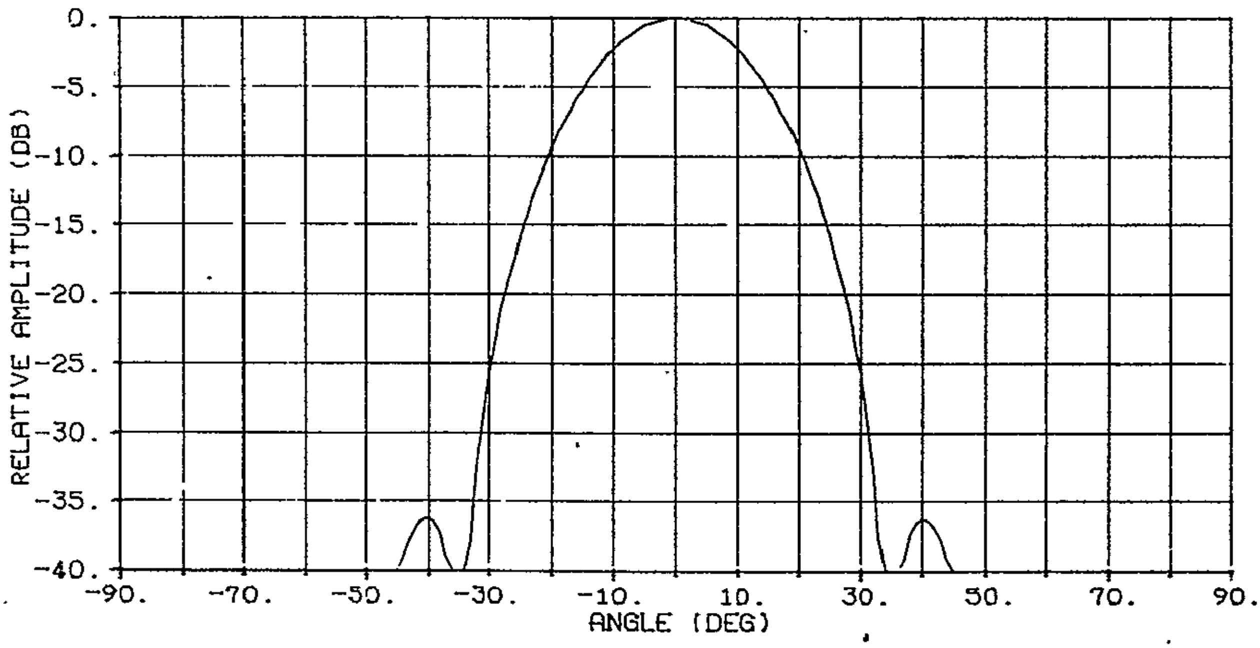


(b) $\phi = 90^{o}$ CUT

Figure 2-23. Four-Element (4 Patches per Element) Feed Cluster Pattern

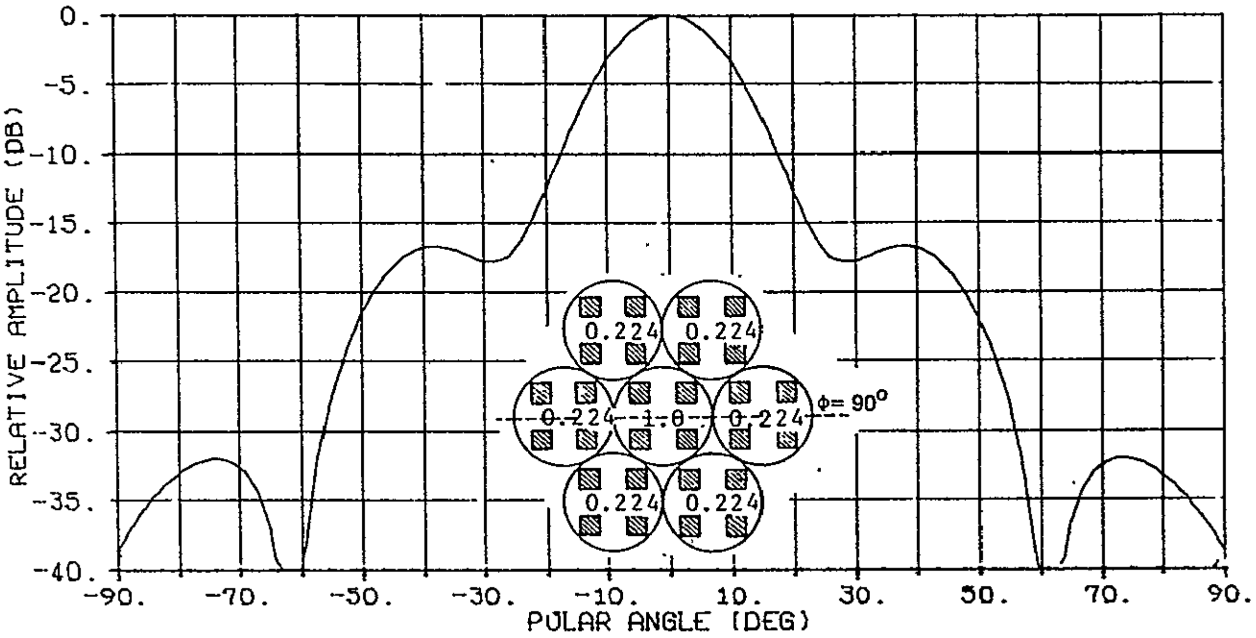


(a) $\phi = 0^{o}$ CUT

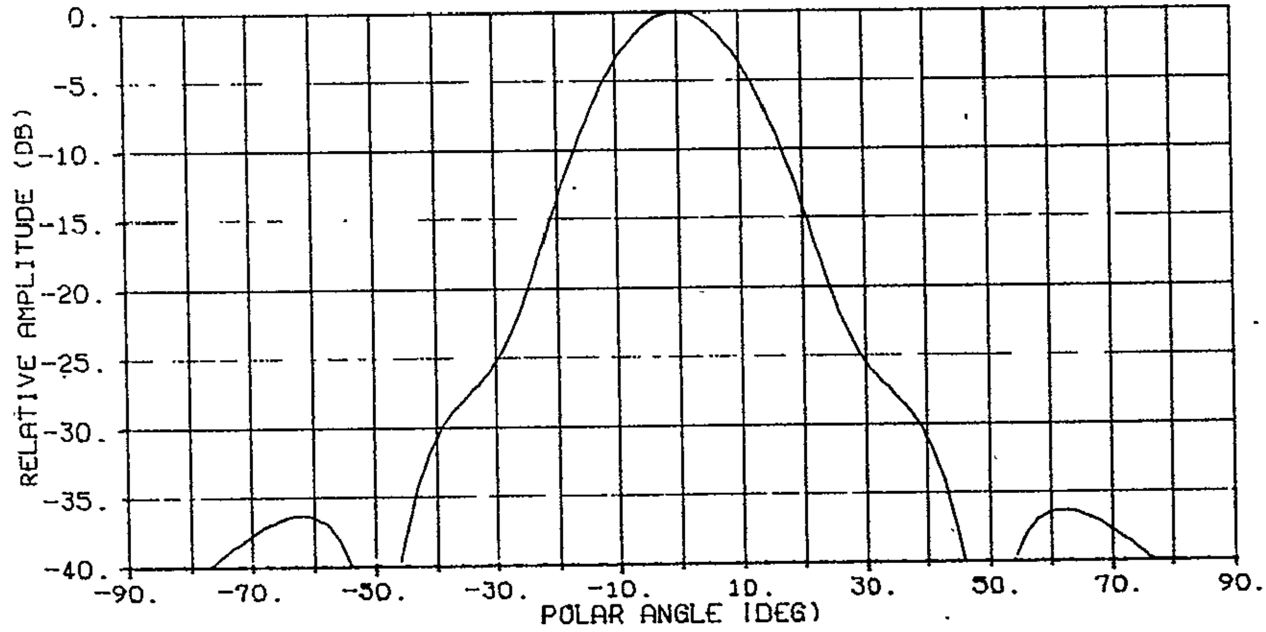


(b) $\phi = 90^{o}$ CUT

Figure 2-24. Six-Element (2 Patches per Element) Feed Cluster Pattern

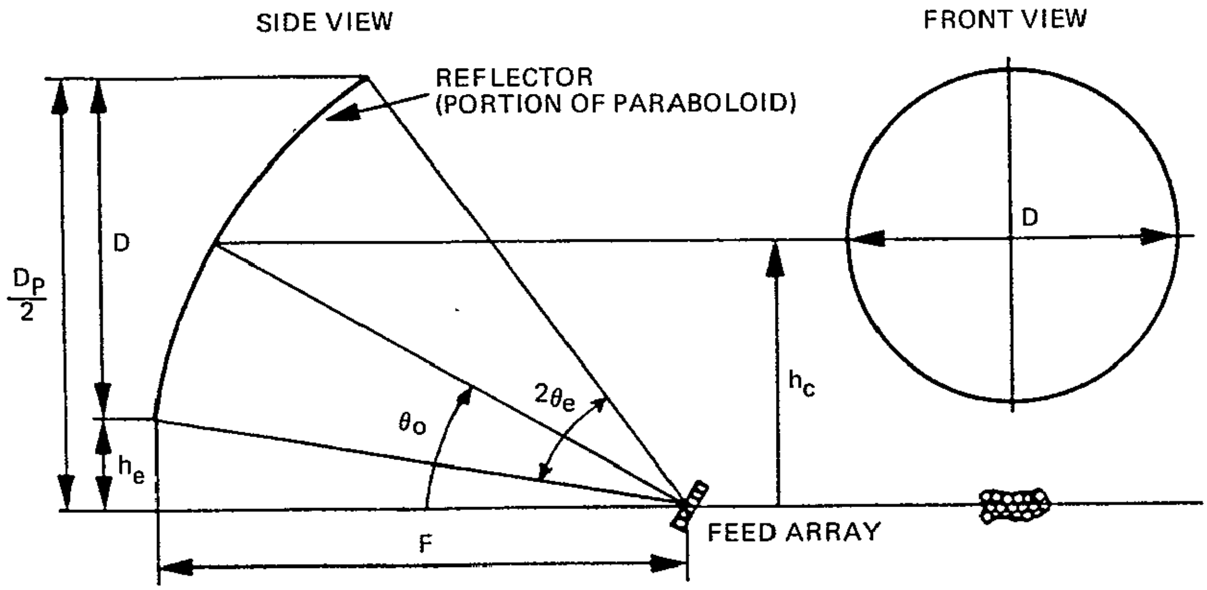


(a) $\phi = 0^{o}$ CUT



(b) $\phi = 90^{o}$ CUT

Figure 2-25. Seven-Element (4 Patches per Element) Feed Cluster Pattern



$D = 15m$

$F = 15m, F/D = 1$

$h_e = 1.5m$

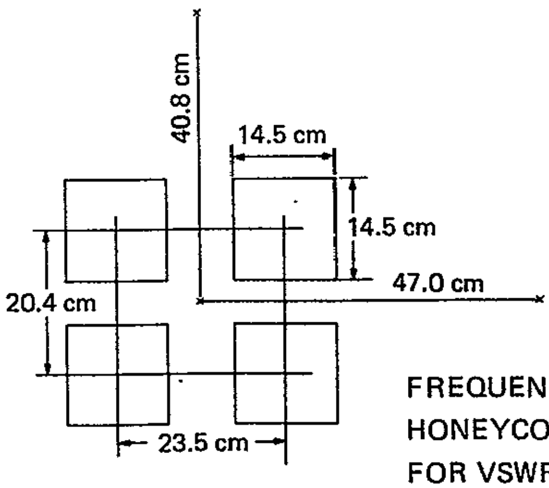
$h_c = 9.0m$

$D_p = 33m, F/D_p = 0.45$

$\theta_o = 33.4^o$

$2\theta_o = 51.9^o$

(a) REFLECTOR

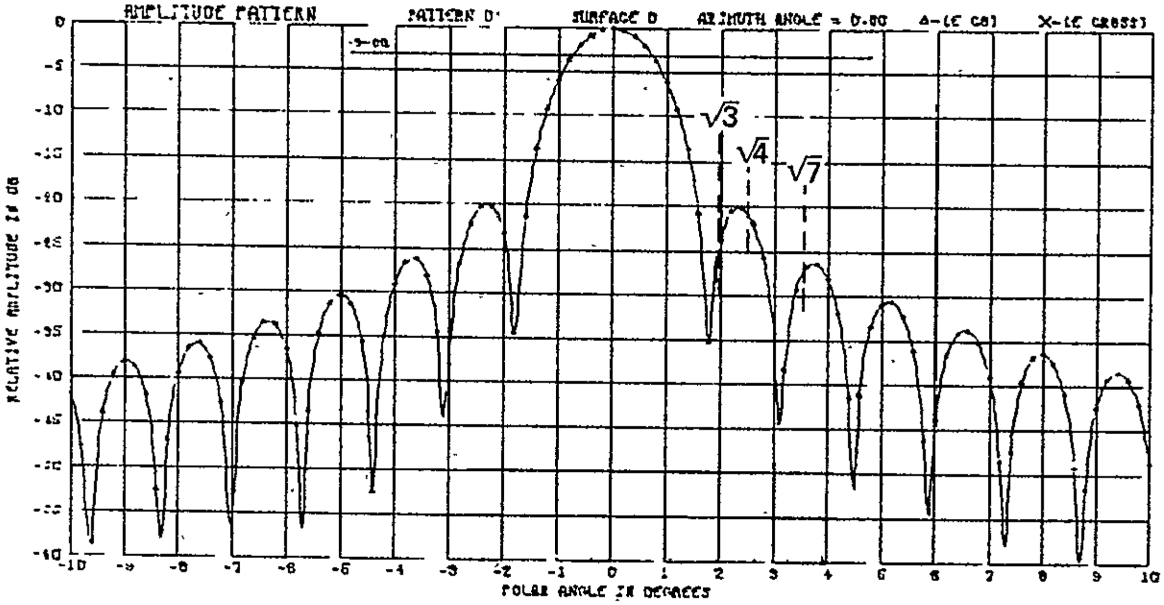


FREQUENCY: 845.5 MHz, WAVELENGTH: 35.5 cm
HONEYCOMB SUBSTRATE – THICKNESS: 1.8 cm
FOR VSWR = 1.5 – DIELECTRIC CONSTANT: 1.17
POLARIZATION: CIRCULAR

(b) FEED ELEMENT COMPOSED OF MICROSTRIP PATCHES

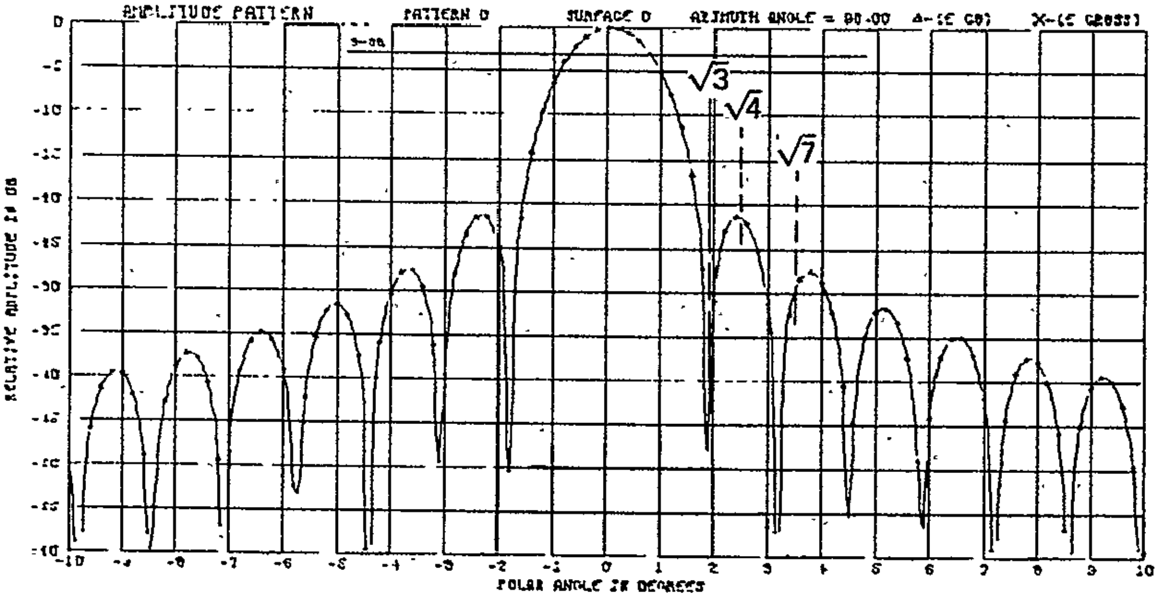
Figure 2-26. Feed/Reflector Parameters for the 15-m UHF Antenna of MSAT-2

D=42.3.F=42.3.HC=25.4.OMEG=146.6
BEAM DIRECTION:THETR= .00 PHIR= .00 GAIN= 40.84 EFFICIENCY= 68.67%
PATTERN AXIS:THETB= .00 PHIB= .00 PATTERN PLANE: PHI= .00
LEFT CIRCULAR POLARIZATION



(a) $\theta = 0^{\circ}$ CUT

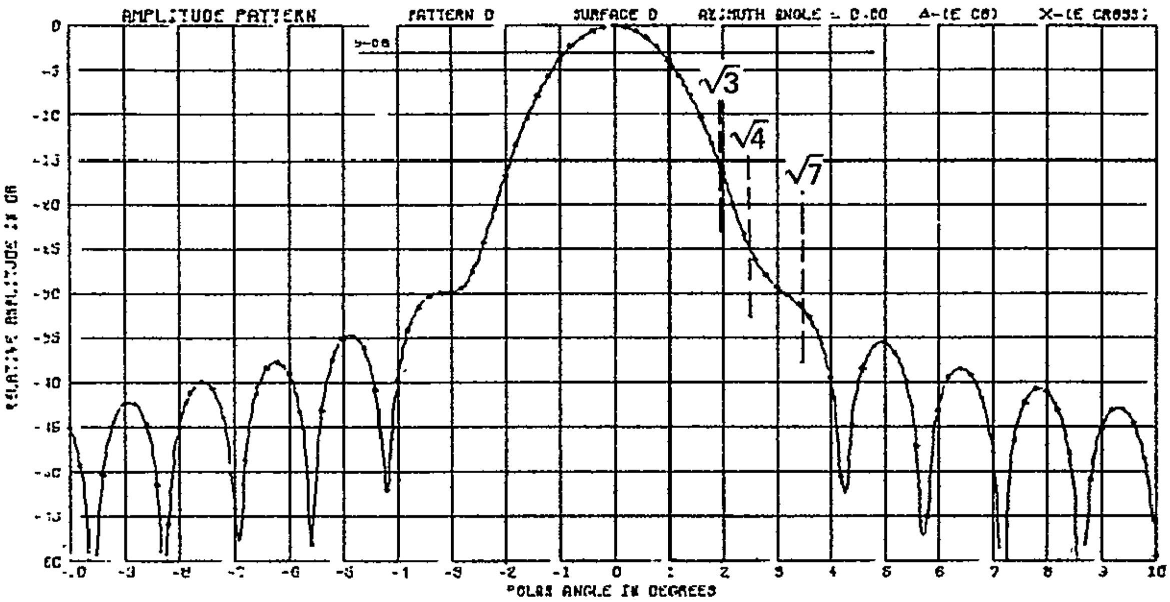
D=42.3.F=42.3.HC=25.4.OMEG=146.6
BEAM DIRECTION:THETR= .00 PHIR= .00 GAIN= 40.84 EFFICIENCY= 68.67%
PATTERN AXIS:THETB= .00 PHIB= .00 PATTERN PLANE: PHI= 90.00
LEFT CIRCULAR POLARIZATION



(b) $\theta = 0^{\circ}$ CUT

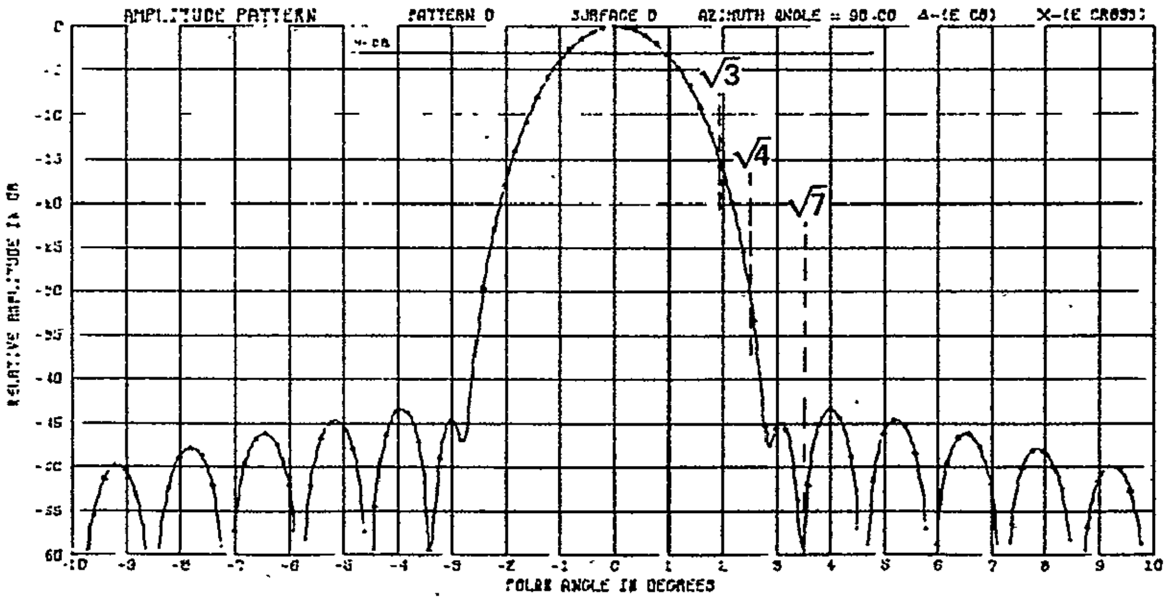
Figure 2-27. Pattern of the 15-Meter Antenna with Single-Element Feed

D=42.3.F=42.3.HC=25.4.CMEG=146.6
BEAM DIRECTION:THETR= .CO PHIR= .OO GAIN= 40.31 EFFICIENCY= 60.80%
PATTERN AXIS:THETB= .CO PHIB= .CO PATTERN PLANE: PHI= .OO
LEFT CIRCULAR POLARIZATION



(a) θ = 0° CUT

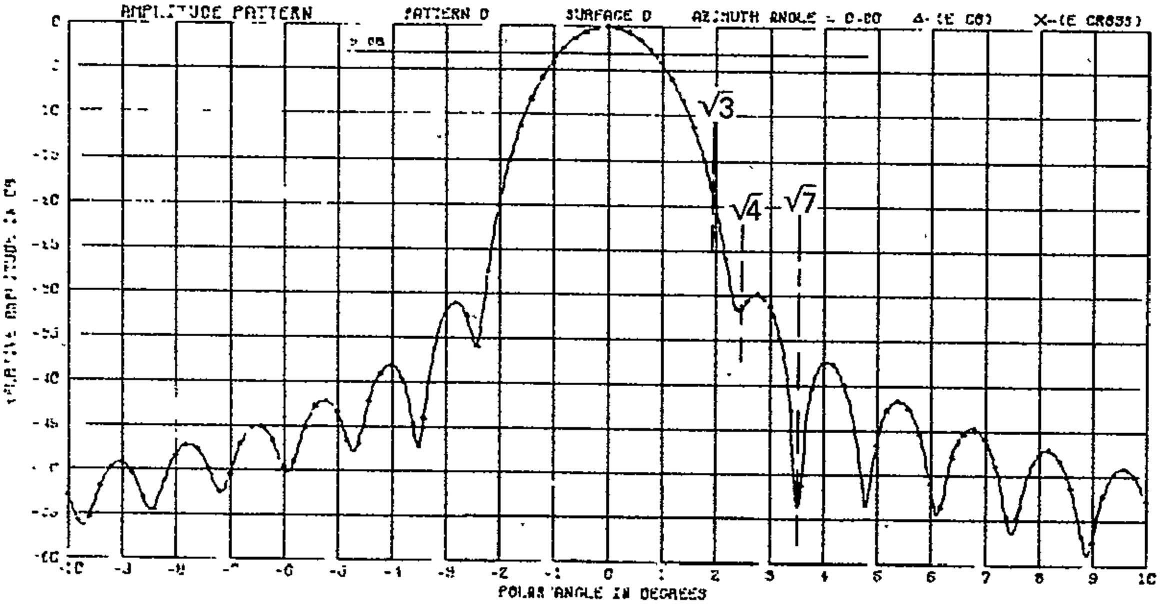
D=42.3.F 42.3.HC=25.4.CMEG=146.6
BEAM DIRECTION:THETR= .CO PHIR= .CO GAIN= 40.31 EFFICIENCY= 60.80%
PATTERN AXIS:THETB= .CO PHIB= .OO PATTERN PLANE: PHI= 90.CO
LEFT CIRCULAR POLARIZATION



(b) θ = 90° CUT

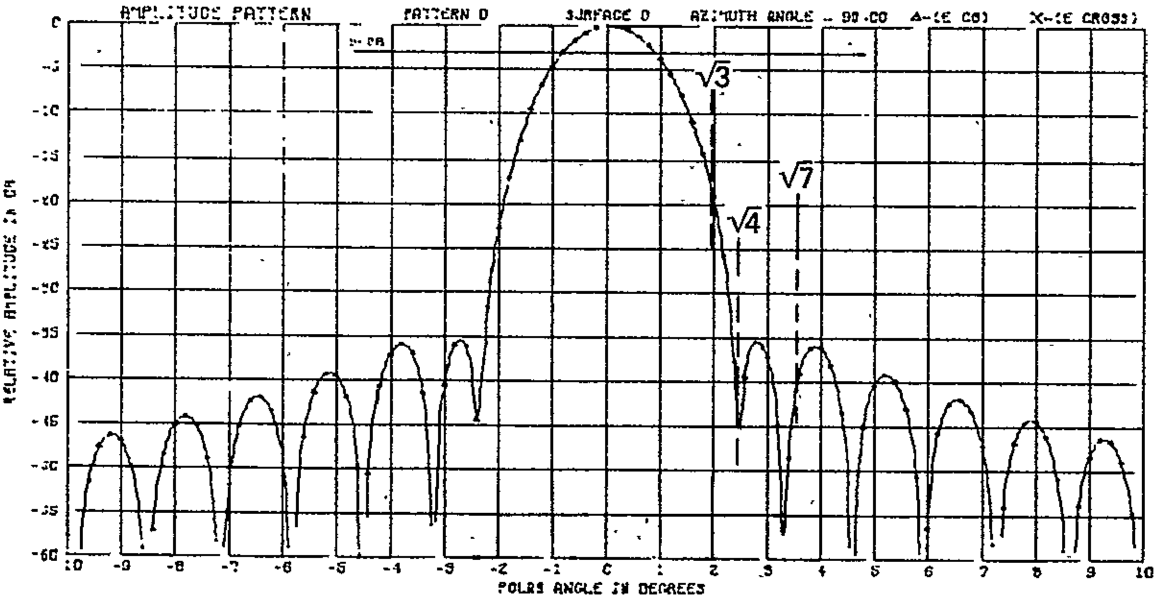
Figure 2-28. Pattern of the 15-Meter Antenna with 4-Element Feed

G=42.3.F=42.3.HC=25.4.OMEG=146.6
BEAM DIRECTION:THETR= .CO PHIR= .CO GAIN= 40.66 EFFICIENCY= 65.95%
PATTERN AXIS:THETB= .CO PHIB= .CO PATTERN PLANE: PHI= .CO
LEFT CIRCULAR POLARIZATION



(a) $\theta = 0^{o}$ CUT

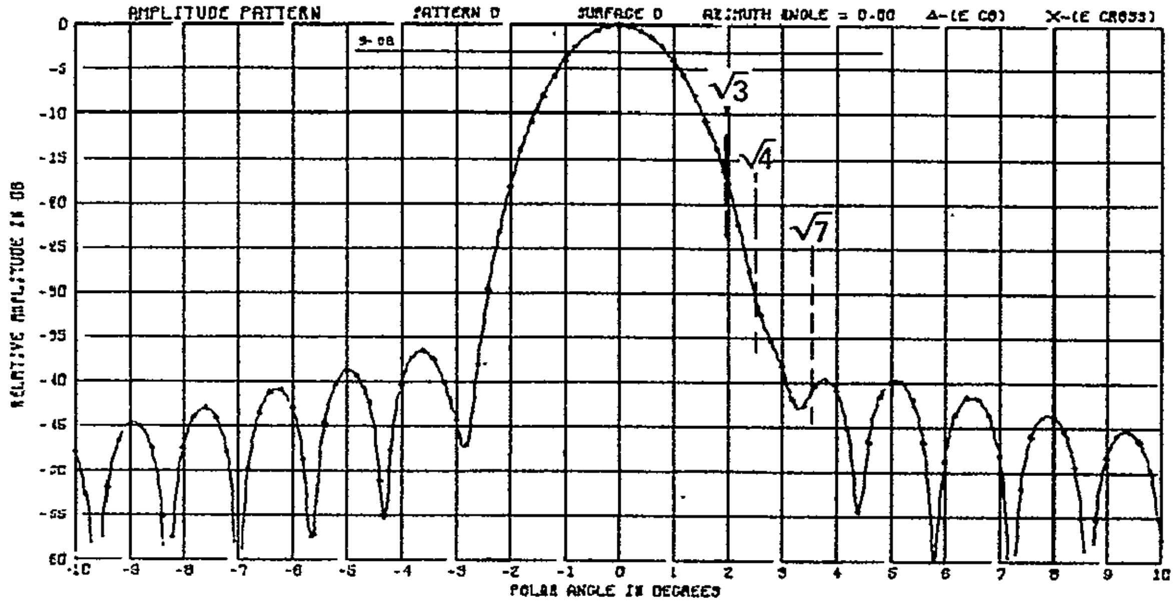
G=42.3.F=42.3.HC=25.4.OMEG=146.6
BEAM DIRECTION:THETR= .CO PHIR= .CO GAIN= 40.66 EFFICIENCY= 65.95%
PATTERN AXIS:THETB= .CO PHIB= .CO PATTERN PLANE: PHI= 90.CO
LEFT CIRCULAR POLARIZATION



(b) $\theta = 90^{o}$ CUT

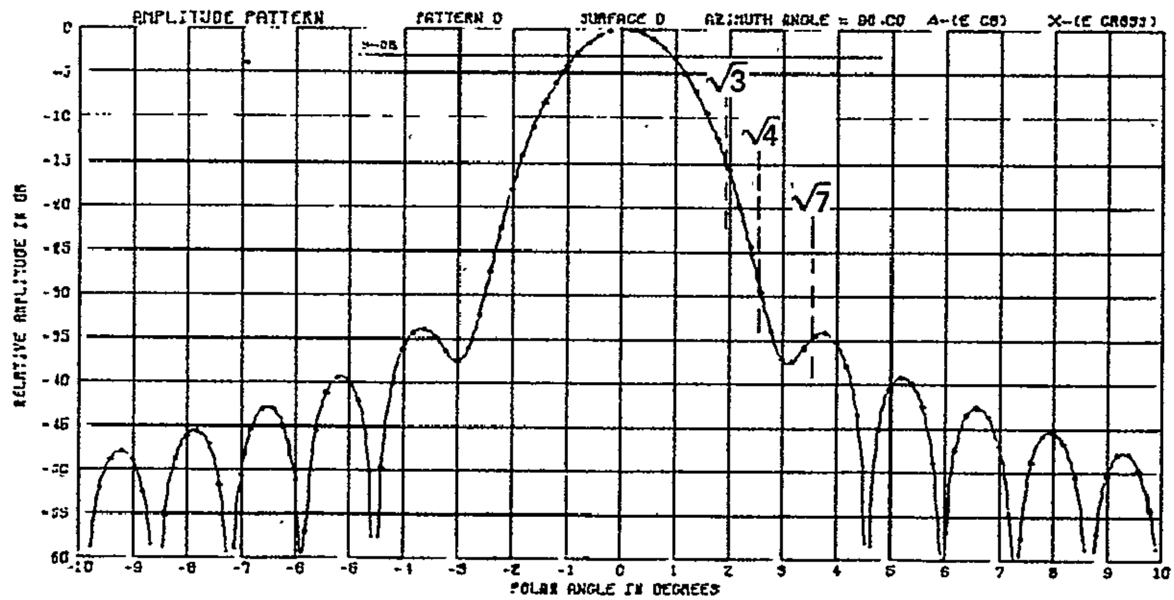
Figure 2-29. Pattern of the 15-Meter Antenna with 6-Element Feed

D=42.3.F=42.3.HC=25.4.OMEG=146.6
BEAM DIRECTION:THETR= .00 PHIR= .00 GAIN= 40.32 EFFICIENCY= 60.93%
PATTERN AXIS:THETB= .00 PHIB= .00 PATTERN PLANE: PHI= .00
LEFT CIRCULAR POLARIZATION



(a) θ = 0° CUT

D=42.3.F=42.3.HC=25.4.OMEG=146.6
BEAM DIRECTION:THETR= .00 PHIR= .00 GAIN= 40.32 EFFICIENCY= 60.93%
PATTERN AXIS:THETB= .00 PHIB= .00 PATTERN PLANE: PHI= 90.00
LEFT CIRCULAR POLARIZATION



(b) θ = 90° CUT

Figure 2-30. Pattern of the 15-Meter Antenna with Seven-Element Feed

On the negative side, the beam-broadening effect also includes the broadening of the shoulders of the main beam to the extent that it can be at the position of the first sidelobe in a single-element feed case (in a sense the main lobe has swallowed the first sidelobe!). Again this means that if the separation between adjacent beams is maintained at the original level, no advantage might be gained (and indeed might be lost in some cases) in terms of better isolation in a low frequency reuse case (3 or 4), since instead of the sidelobes, the shoulders of the main lobe might be interfering with adjacent cochannel beams. Indeed this could be the case even if the beams are moved further apart to a new position such that the adjacent beams touch at the 3-dB level. In Figs. 2-27 through 2-30 the positions of the edge of the nearest cochannel beam in the 3, 4, and 7 frequency reuse scheme are marked.

Based on the above observations and in light of the fact that any multi-element overlapping cluster feed will require a fairly complicated and extensive beam-forming network, it can be concluded that a single-element feed (with one or more subelements) should be looked upon as a preferred candidate, provided that the sidelobes of the secondary far-field pattern and the resulting isolation levels are acceptable. However, if this is not the case then the 6-element configuration seems to provide a good alternative. Both the 4- and 6-element configurations have the added advantage (over the 7-element cluster) that their beam-forming network can be accomplished relatively simply and in a single layer of microstrip or stripline network as shown in Figs. 2-31 and 2-32. Whereas the 7-element cluster requires a two-layered network (as detailed in [6], [9], and [10]). On the other hand, the 7-element cluster has the advantage of higher flexibility because

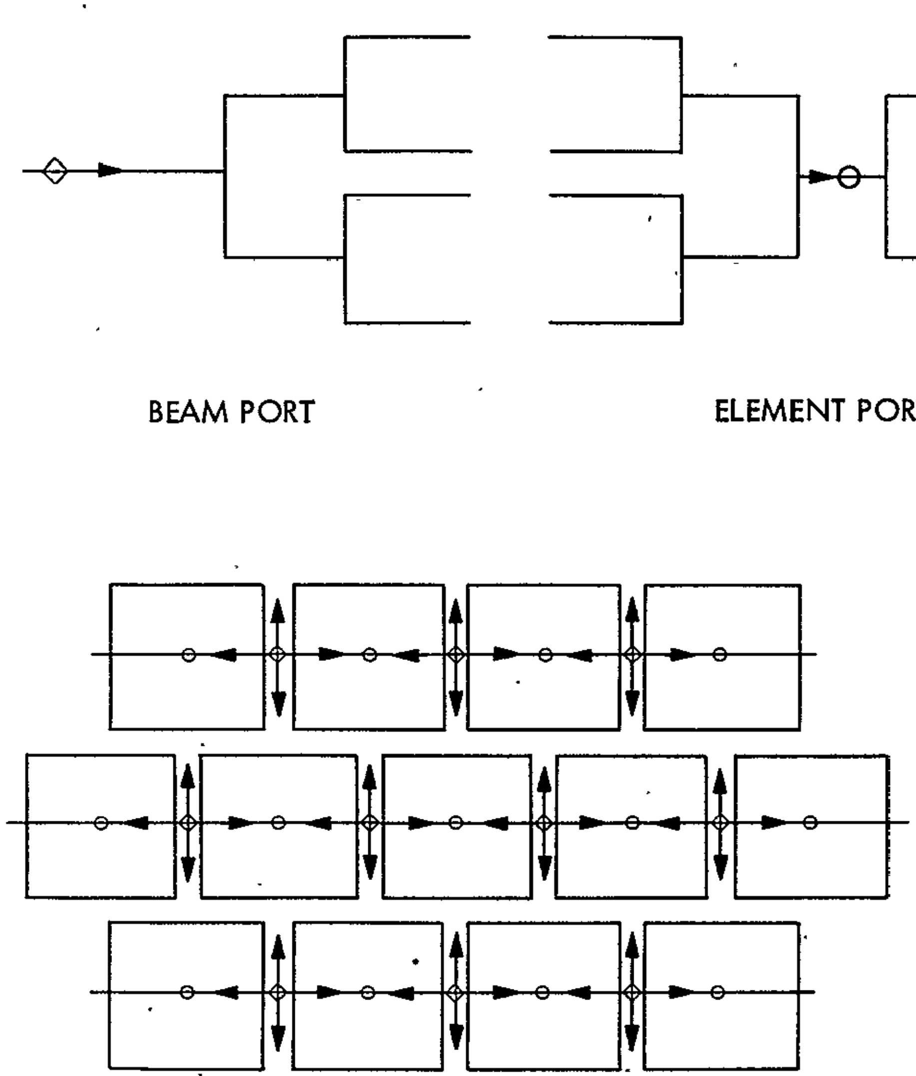


Figure 2-31. Beam-Forming Network Concept for 4-Element Cluster Feed

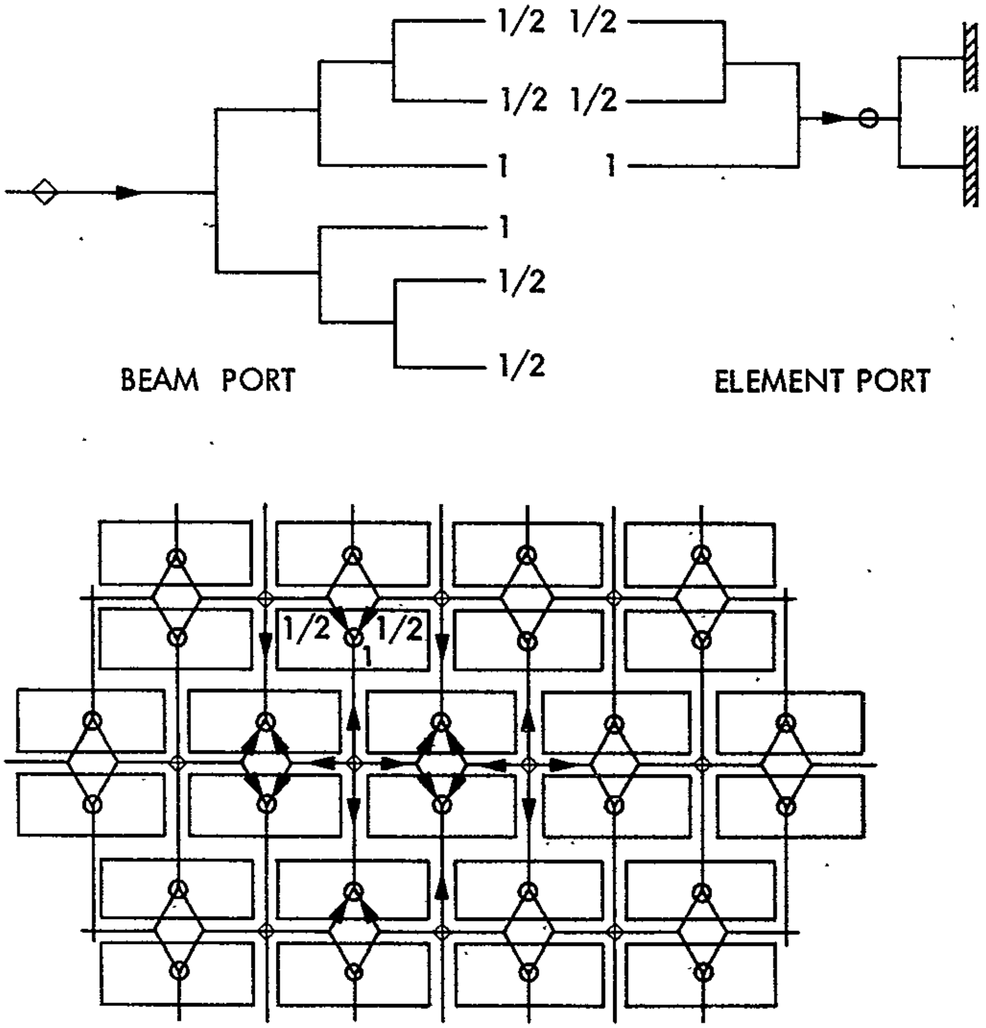


Figure 2-32. Beam-Forming Network Concept for 6-Element Cluster Feed

of the larger number of elements and the additional degrees of freedom that it provides in terms of phase and amplitude adjustments.

The overall area of the feed array in a multibeam system is given approximately by

$$S = \frac{1}{b} F [1 + (h_c/4F)^2] A \qquad (2\text{-}4)$$

in which F is the antenna focal length, b is the beam deviation factor (less than but close to unity), h_c is the offset height of the center of the reflector (equal to zero for a symmetric reflector), and A is the spatial angle of the coverage region in steradians. Since in most cases h_c is much smaller than 4F and b is close to unity, the following interesting observations can be made:

a) The feed array dimensions depend mainly on
   1. The angular dimensions of the coverage region, and
   2. The focal length of the reflector.

b) The feed array size is practically independent of
   1. The frequency or wavelength of operation, and
   2. The number of beams over the coverage region.

The size of the overall feed array is somewhat larger in the multi-element overlapping cluster case due to the additional elements needed on the periphery of the array. In the actual cases considered, of course, the dimensions of the overall array panel are calculated accurately and in a detailed fashion for each individual case.

2.7.3 Interbeam Isolation

In a frequency-reuse multibeam system a number of beams which are spaced apart by a few beamwidths can operate at the same frequency. The number of these

cochannel beams, their separation, and the pattern characteristics of each beam must be such that the interference at any beam due to the other beams remains below a certain specified level compared to the desired signal level. A performance index commonly employed is C/I, the ratio of the desired carrier signal to the incoherent (power) sum of all the interfering signals. However a distinction must be made between the uplink and downlink interference.

The two situations are presented in Fig. 2-33. In the uplink case as seen in Fig. 2-33(a), the interfering signals come from ground transmitters located in the cochannel beam footprints and enter the satellite receiver through the sidelobes of the desired beam. Thus, only one beam pattern is involved in the process. Since the transmitted signals come from different geographical locations on the ground, they are subject to different multipath, tropospheric, ionospheric, space loss, and other effects associated with their paths. Therefore, they should be included in the isolation calculation. In general due to the fact that the desired signal might be more severely affected by these effects than the undesired interferers, the uplink C/I could be much worse than expected. Furthermore, since the desired and interfering transmitters could be at various locations in their respective footprints, the calculation of C/I for all situations could be very complicated and time consuming. Perhaps only an upper bound on interference, when the signal contributes the least and the interferers the most, can be realistically calculated.

The downlink interference situation is rather different. As seen in Fig. 2-33(b), the single receiver at a point within the footprint of the desired beam receives interference from other beams.

In this case only a single path is involved; therefore, the various path loss mechanisms affect the signal and the interferers identically and do not affect the C/I calculations. The interference, however, comes from different cochannel beams, and all of them are involved in the calculation of the C/I. Since the

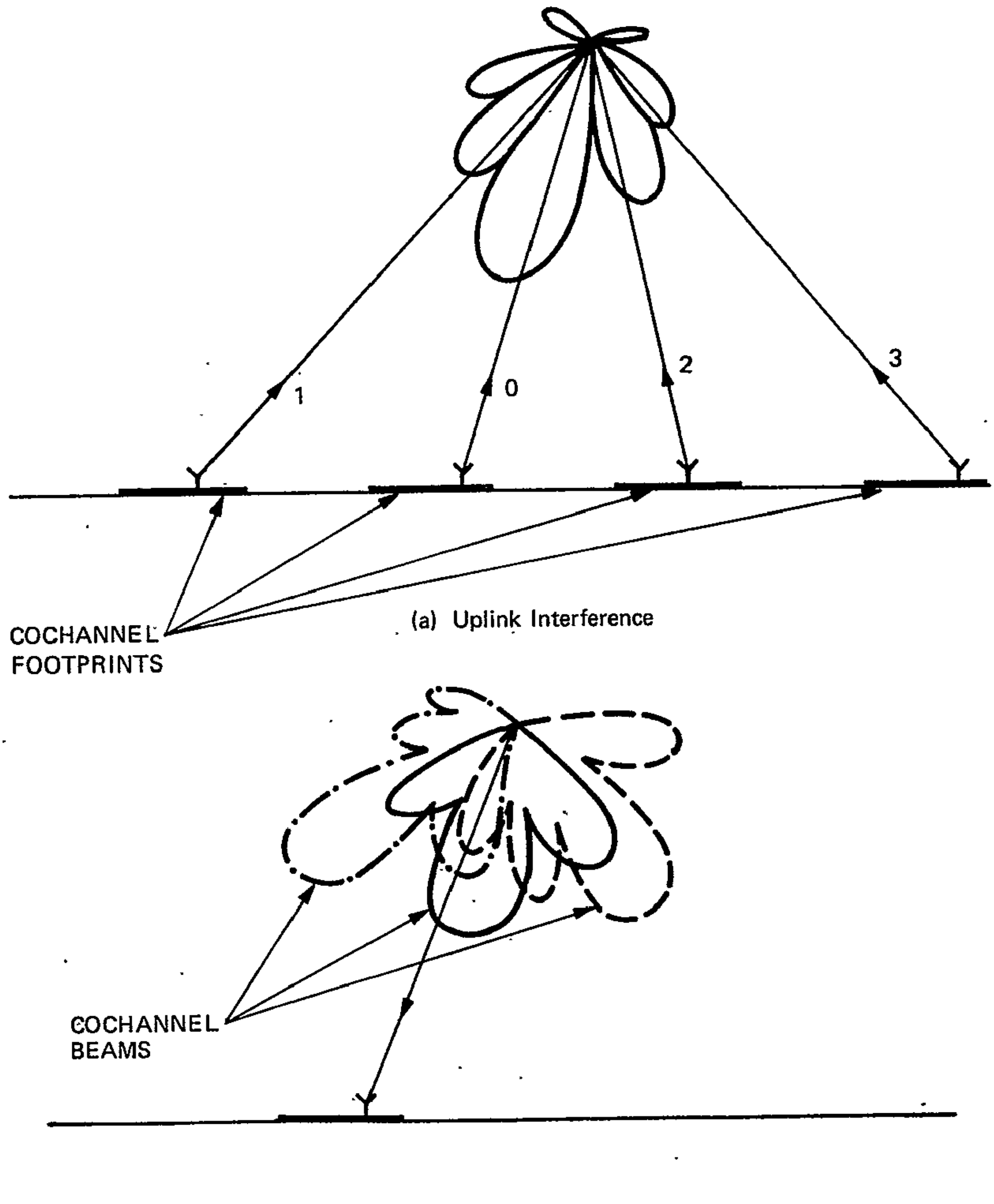


Figure 2-33. Multibeam Signal Interference

position of beams, with respect to each other is fixed, only one set of calculations needs to be performed in order to obtain the isolation at different points within the desired footprint. In this study only the downlink C/I is considered and it is assumed that the uplink has a more or less equivalent value. The effects of multipath, etc., are considered separately.

Many multibeam cases including 10-, 15- and 20-meter diameter reflectors at high UHF frequencies (821 to 870 MHz) and 10- and 15-meter diameter reflectors at L-band (1.55 to 1.65 GHz) with various frequency reuse schemes have been considered. Figs. 2-34 through 2-36 show the beam layouts and frequency reuse schemes for a 15-meter reflector at 90° and 130° west longitude geostationary orbits operating at 823 MHz. Geometric characteristics and typical far-field patterns of this antenna were given in Figs. 2-26 through 2-30. An array configuration for this antenna with 12 beams at 90° west longitude is given in Fig. 2-37. Figs. 2-38 through 2-40 show the multibeam layouts as viewed from a geostationary orbit for a 20-meter antenna operating at 823 MHz at 90° and 130° west longitude geostationary locations with 4, 7, and 9 frequency reuse schemes. The antenna and feed parameters are given in Fig. 3-11.

Summary results of the isolation studies for these 15- and 20-meter UHF antennas are given in Table 2-6. The L-band antennas (1.55 to 1.65 GHz) with 10.6- and 15-meter diameters have also been studied. Beam size and layout of the 10.6-meter antenna are similar to the 20-meter UHF case and will not be repeated. (Elsewhere in this report this 10.6-meter antenna is referred to as the 10-meter antenna.) Figs. 2-41 through 2-42 show the beam layout of the 15-meter L-band antenna at 90° and 130° west longitude geostationary orbit positions with 7 and 9 frequency reuse schemes. Geometric characteristics of 10.6- and 15-meter L-band antennas are shown in Figs. 2-43 and 2-44, respectively. Results of beam isolation studies for these antennas are summarized in Table 2-7. These results are based on RMS surface errors of equal to or less than 1/50th of the wavelength with typical

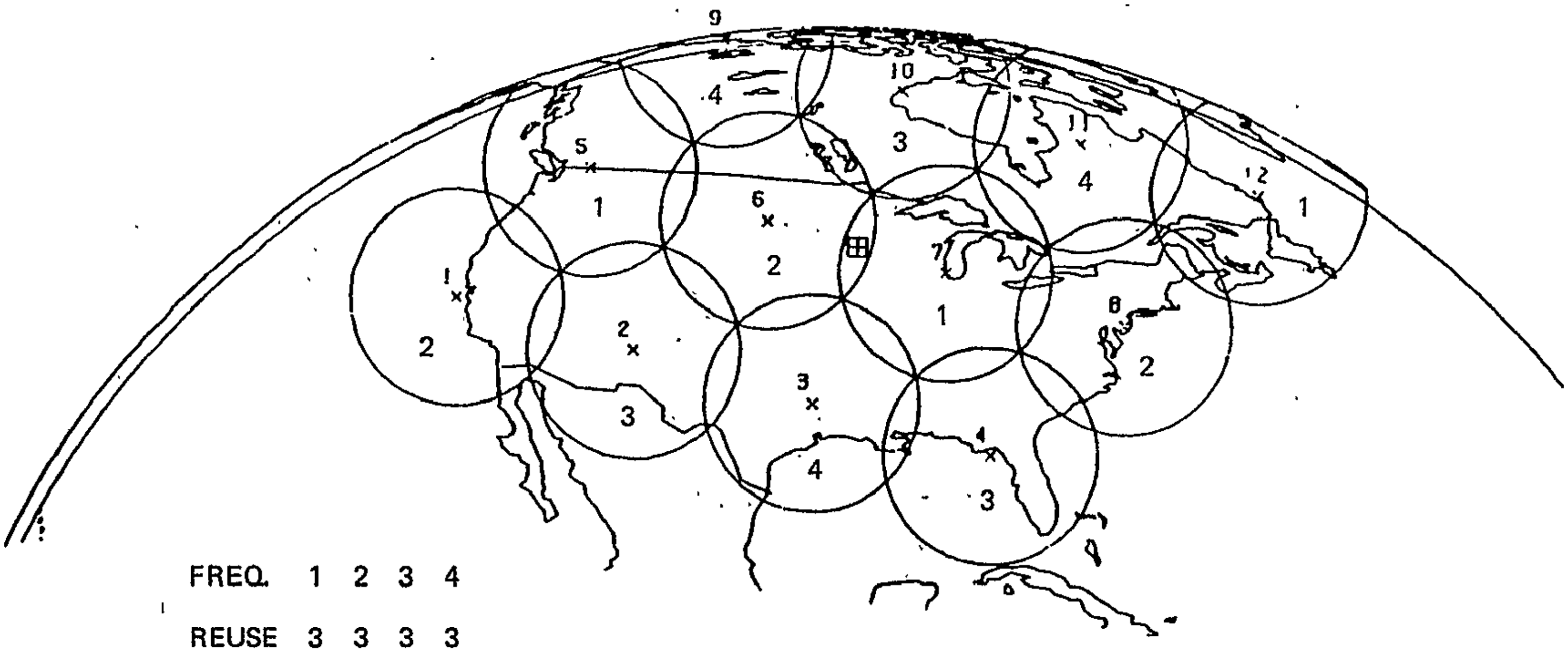


Figure 2-34(a). MSAT-2 Satellite Antenna Beam Layout, 4-Frequency Reuse
Antenna Diameter: 15m; f = 845.5-MHz; Crossover Beamwidth: 1.9°;
Crossover Gain: 35 dB; Satellite Position: 90°W Longitude Geostationary Orbit

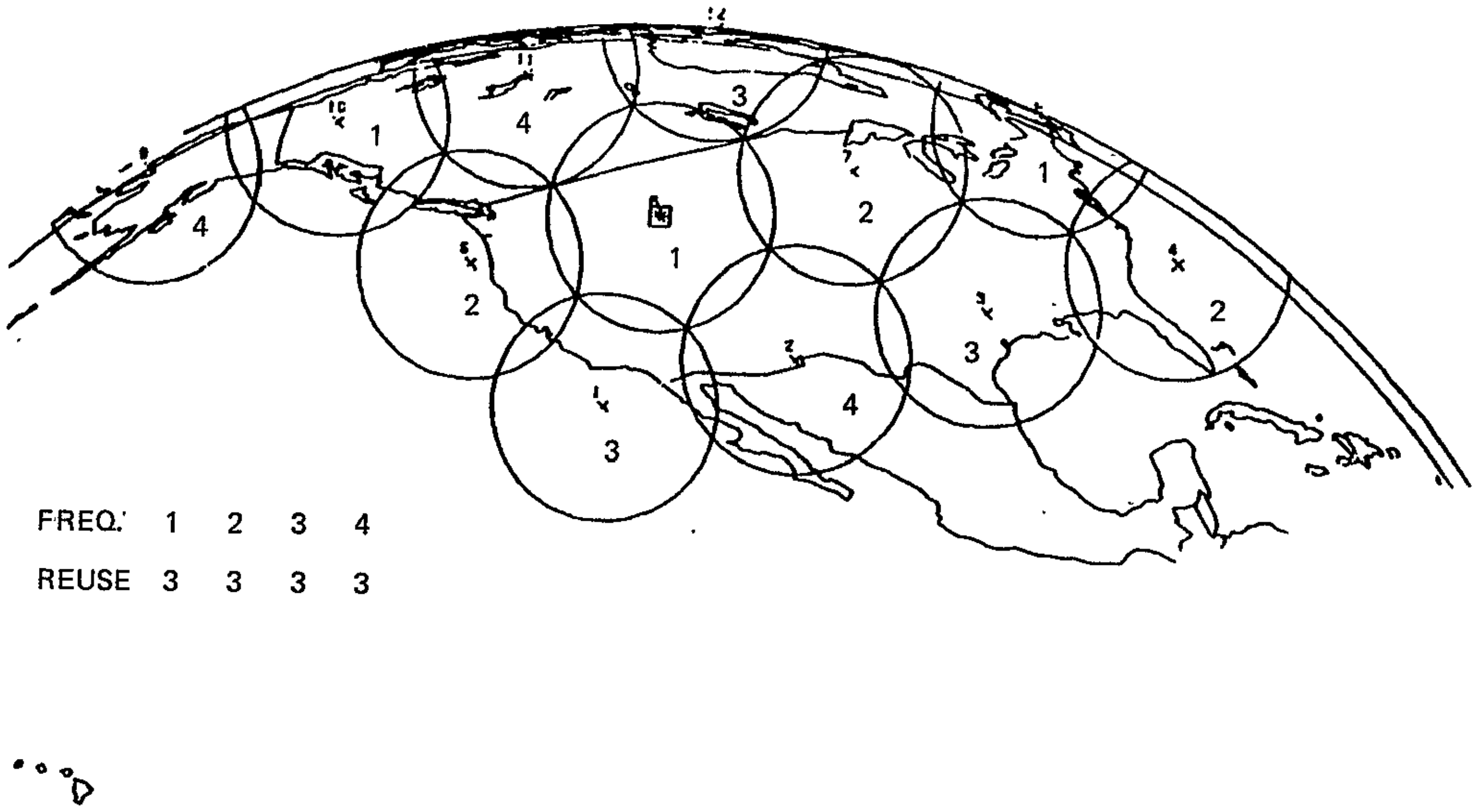
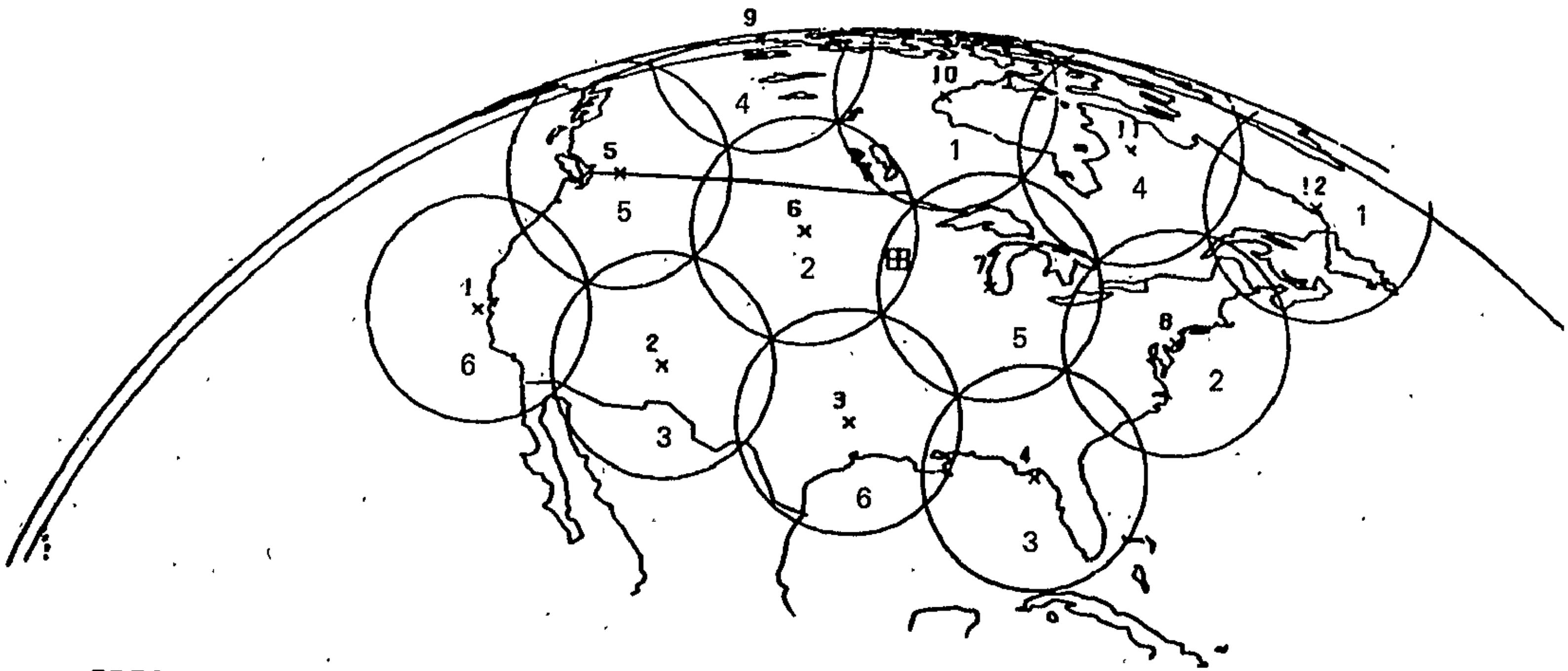


Figure 2-34(b). MSAT-2 Satellite Antenna Beam Layout, 4-Frequency Reuse
Antenna Diameter: 15m; f = 845.5-MHz; Crossover Beamwidth: 1.9°;
Crossover Gain: 35 dB; Satellite Position: 130°W Longitude Geostationary Orbit



FREQ	1	2	3	4	5	6
REUSE	2	2	2	2	2	2

Figure 2-35(a). MSAT-2 Satellite Antenna Beam Layout, 6-Frequency Reuse
Antenna Diameter: 15m; f = 845.5-MHz; Crossover Beamwidth: 1.9°;
Crossover Gain: 35 dB; Satellite Position: 90°W Longitude Geostationary Orbit

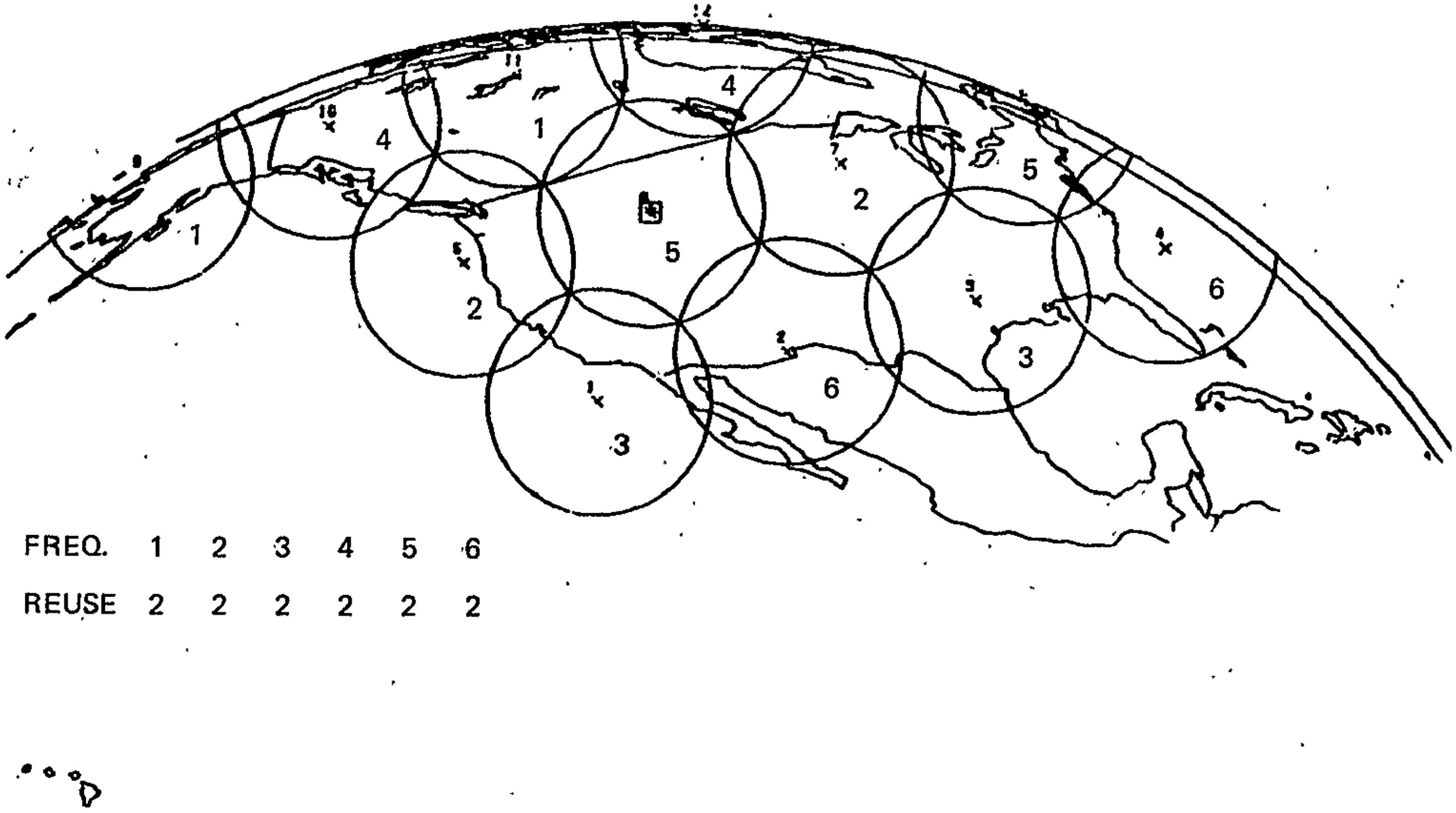
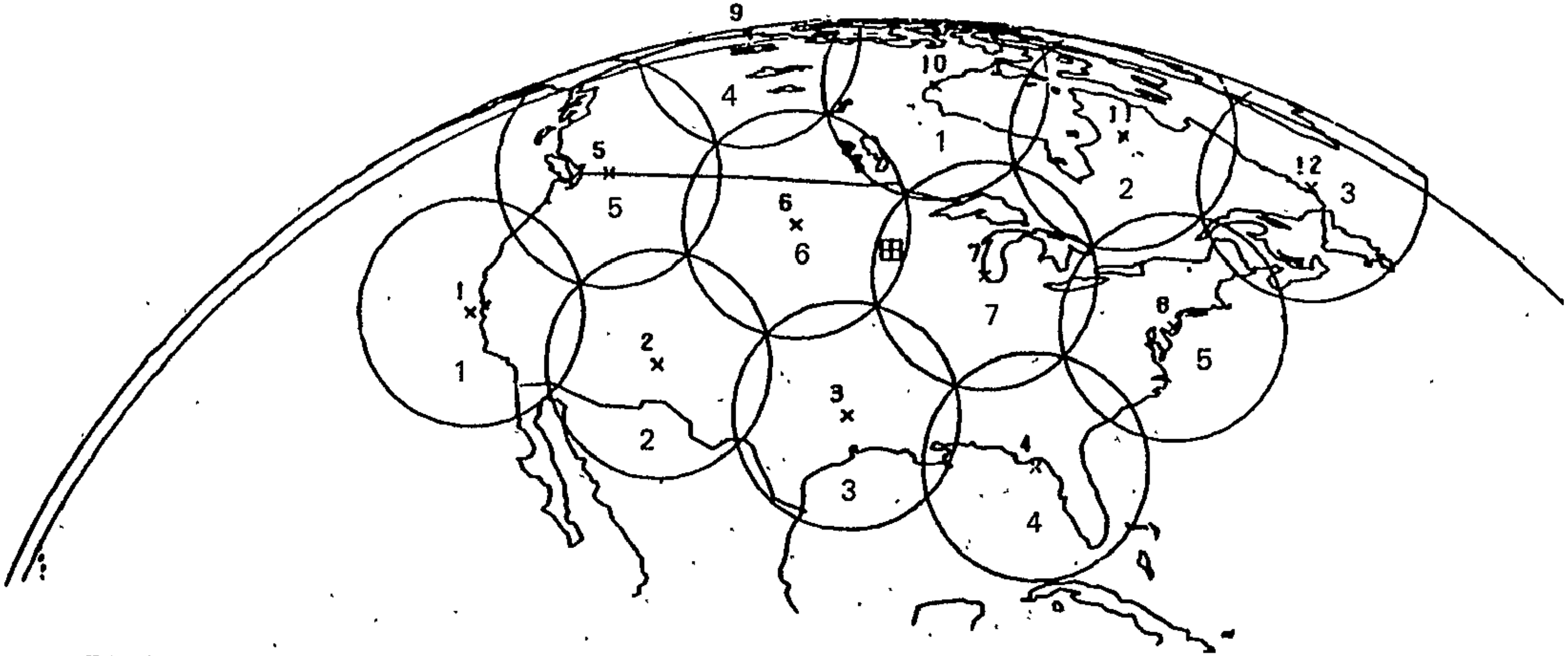


Figure 2-35(b). MSAT-2 Satellite Antenna Beam Layout, 6-Frequency Reuse
Antenna Diameter: 15m; f = 845.5 MHz; Crossover Beamwidth: 1.9°;
Crossover Gain: 35 dB; Satellite Position: 130°W Longitude Geostationary Orbit



FREQ.	1	2	3	4	5	6	7
REUSE	2	2	2	2	2	1	1

Figure 2-36(a). MSAT-2 Satellite Antenna Beam Layout, 7-Frequency Reuse
Antenna Diameter: 15m; f = 845.5-MHz; Crossover Beamwidth: 1.9°;
Crossover Gain: 35 dB; Satellite Position: 90°W Longitude Geostationary Orbit

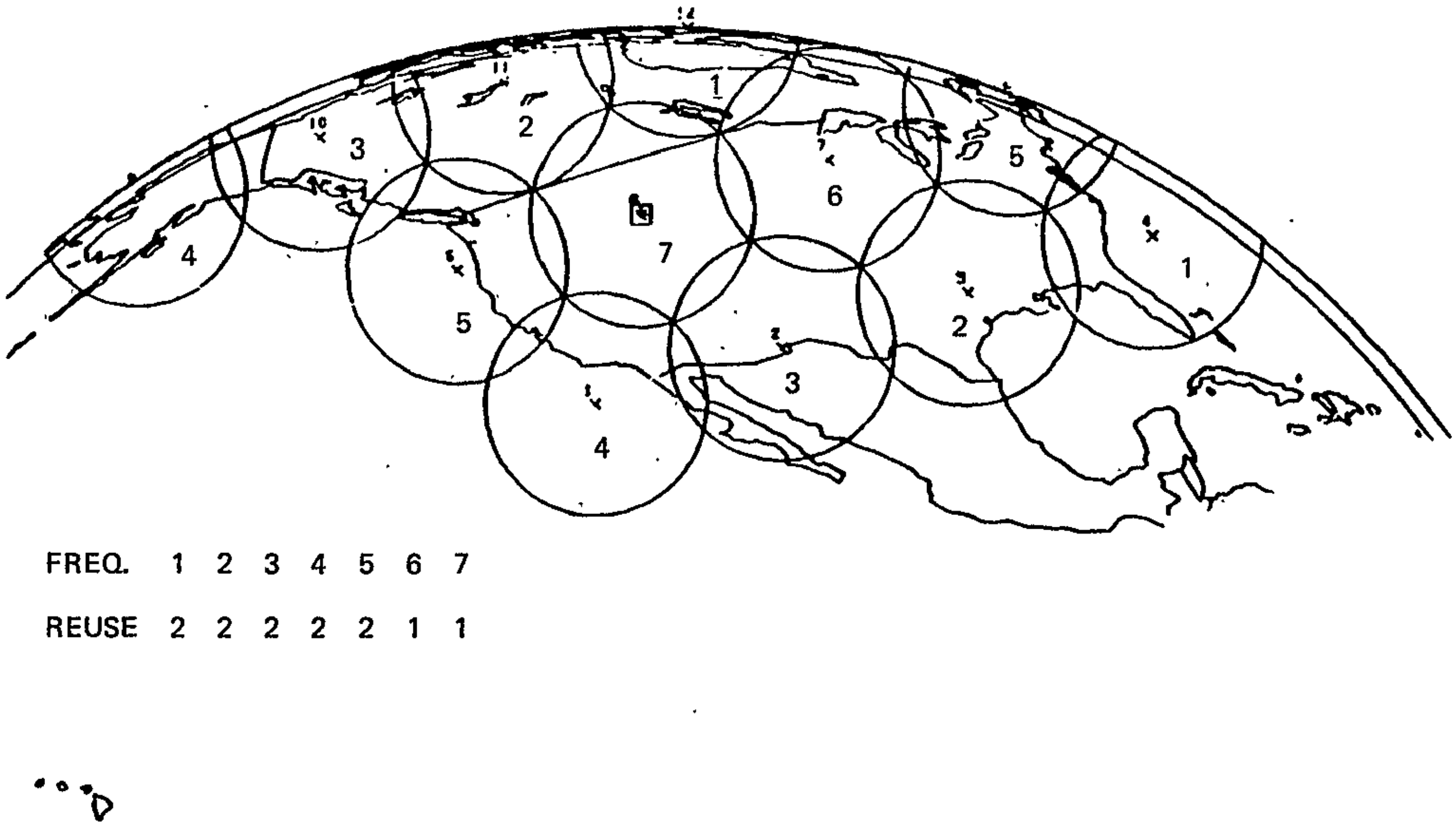
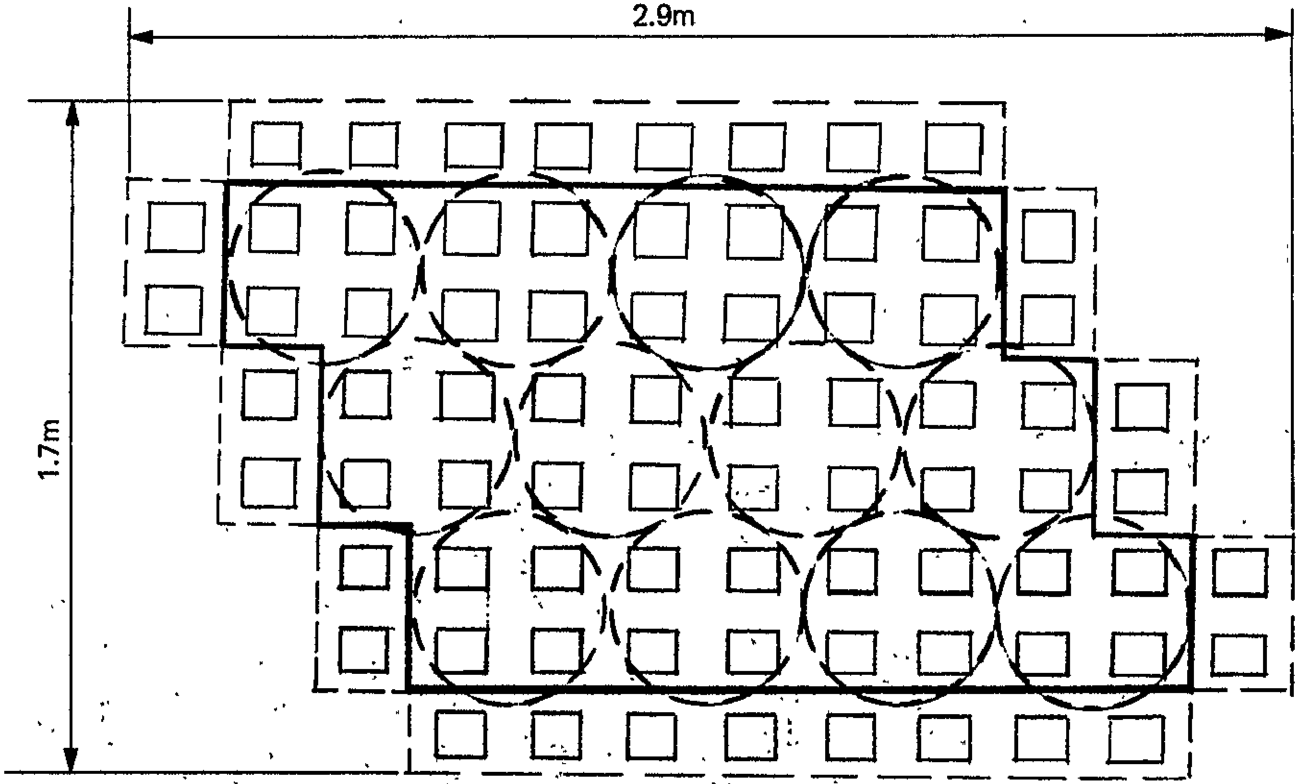


Figure 2-36(b) MSAT-2 Satellite Antenna Beam Layout, 7-Frequency Reuse
Antenna Diameter: 15m; f = 845.5-MHz; Crossover Beamwidth: 1.9°;
Crossover Gain: 35 dB; Satellite Position: 130°W Longitude Geostationary Orbit



(SOLID LINE: SINGLE ELEMENT, DASHED LINE: EXTRA ELEMENTS FOR SIX-ELEMENT CLUSTER)

Figure 2-37. Feed Array Panel Configuration for 12-Beam MSAT-2 Reflector Antenna at 90° West Longitude

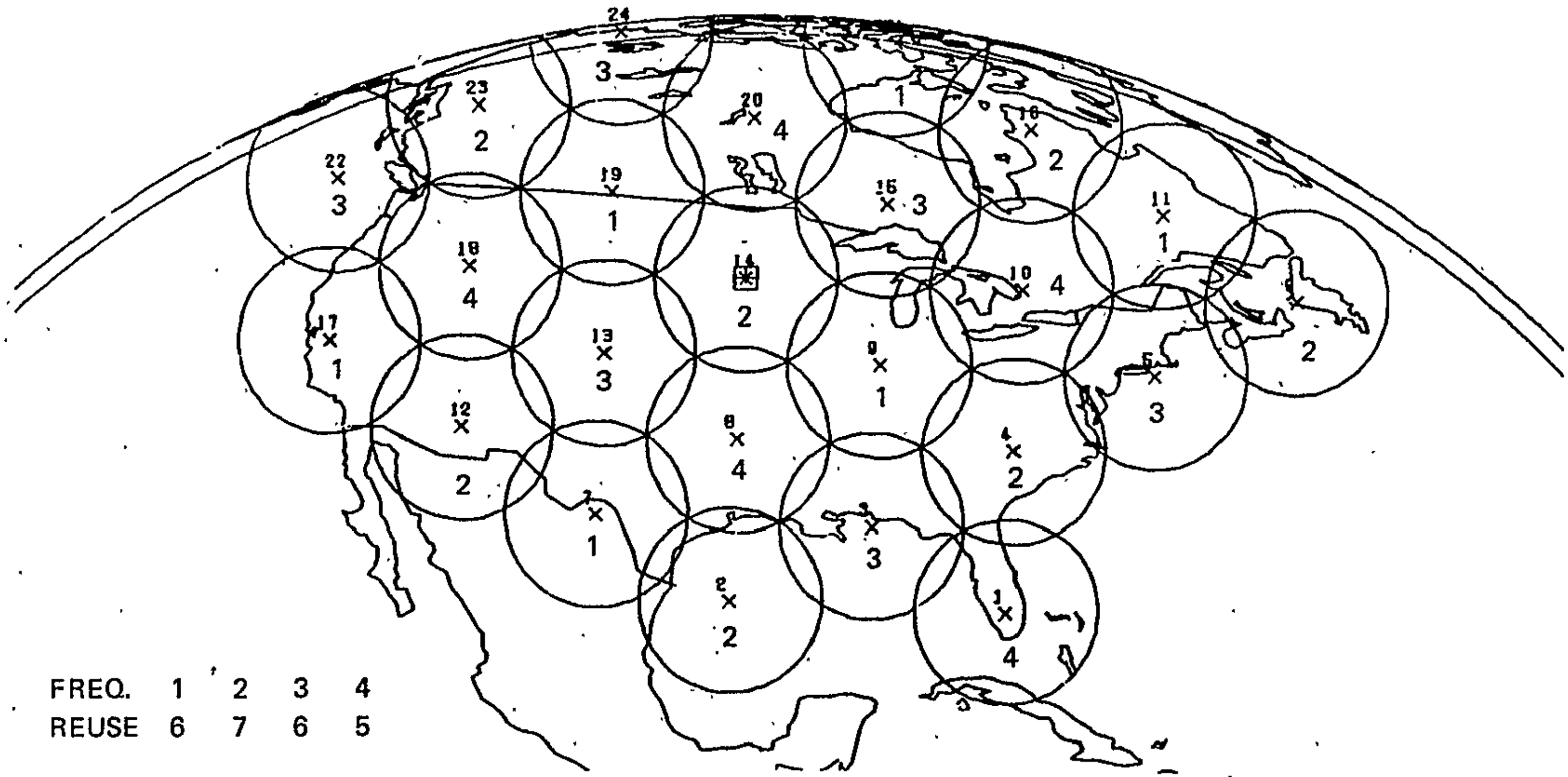


Figure 2-38(a). MSAT-2 Satellite Antenna Beam Layout, 4-Frequency Reuse
Antenna Diameter: 20m; f = 845.5-MHz; Crossover Beamwidth: 1.4°;
Crossover Gain: 37.5 dB; Satellite Position: 90°W Longitude Geostationary Orbit

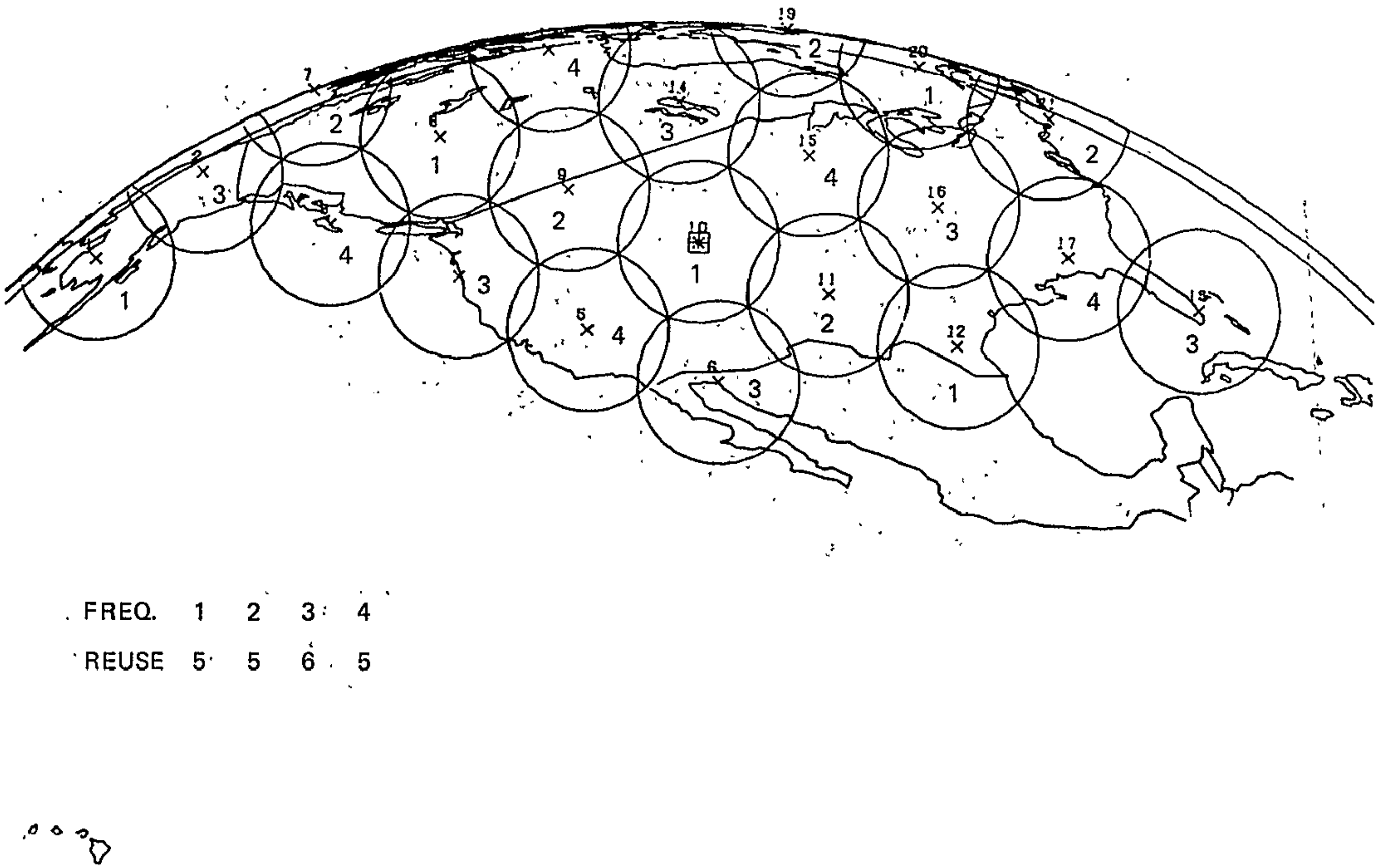


Figure 2-38(b). MSAT-2 Satellite Antenna Beam Layout, 4-Frequency Reuse
Antenna Diameter: 20m; f = 845.5-MHz;Crossover Beamwidth: 1.4°;
Crossover Gain: 37.5 dB;Satellite Position: 130°W Longitude Geostationary Orbit

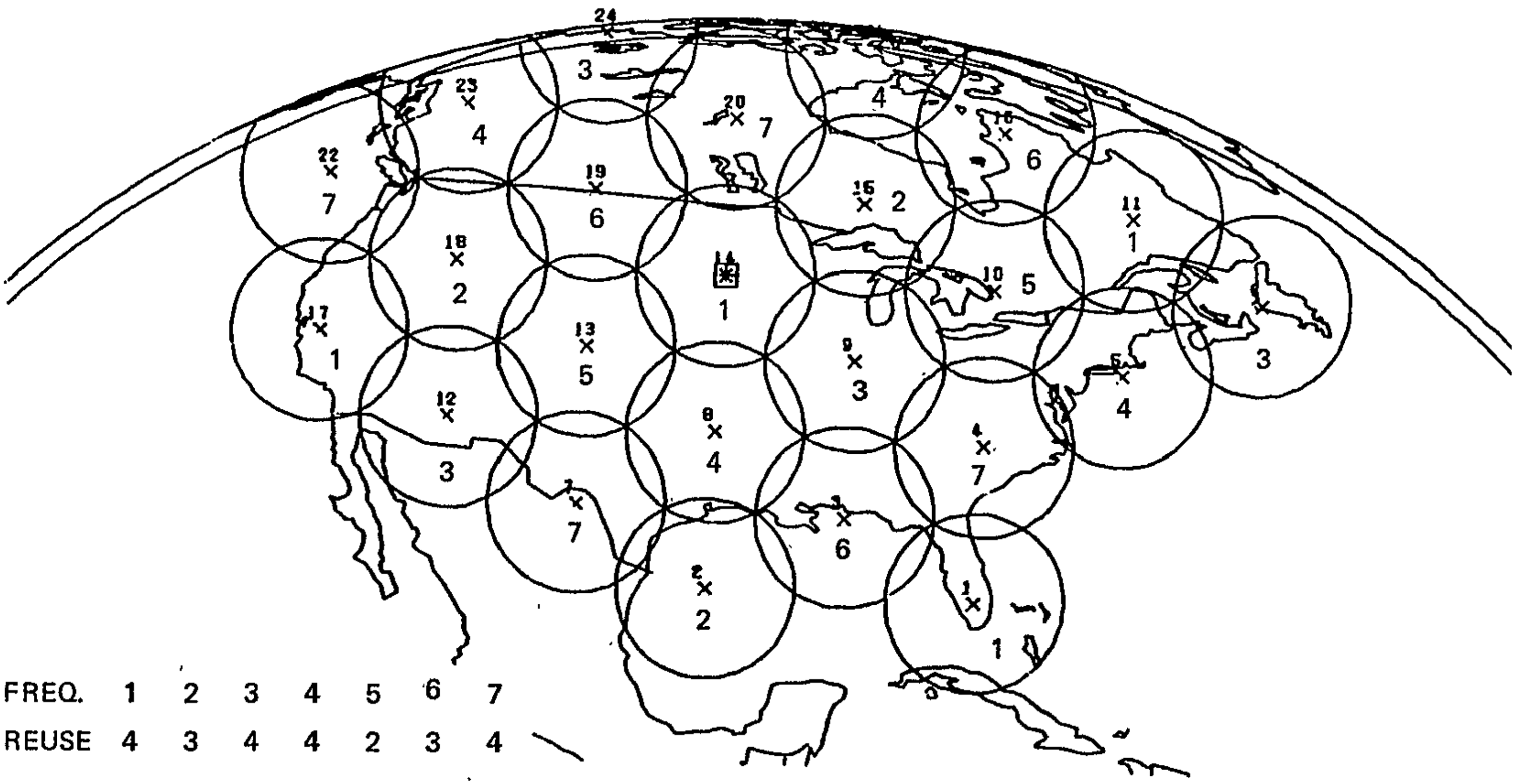
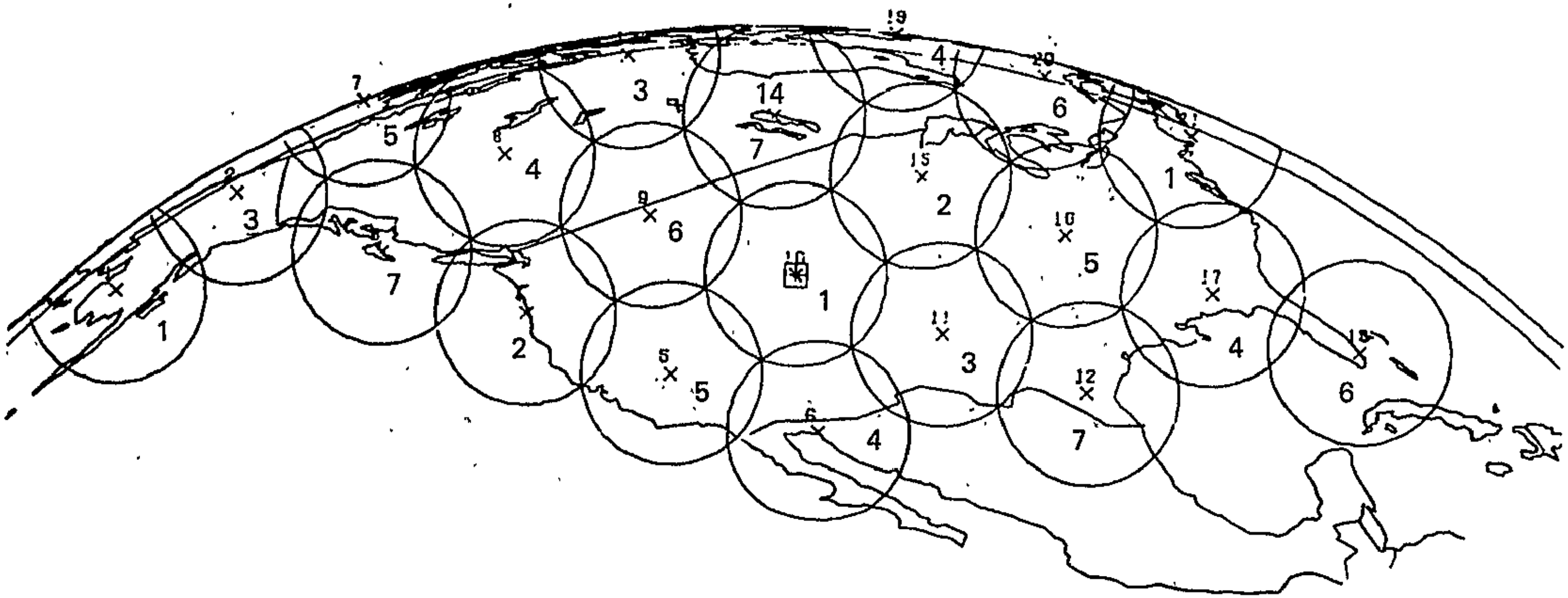


Figure 2-39(a). MSAT-2 Satellite Antenna Beam Layout, 7-Frequency Reuse
Antenna Diameter: 20m; f = 845.5-MHz; Crossover Beamwidth: 1.4°;
Crossover Gain: 37.5 dB; Satellite Position: 90°W Longitude Geostationary Orbit



FREQ.	1	2	3	4	5	6	7
REUSE	3	2	3	4	3	3	3

Figure 2-39(b). MSAT-2 Satellite Antenna Beam Layout, 7-Frequency Reuse
Antenna Diameter: 20m; f = 845.5-MHz; Crossover Beamwidth: 1.4°;
Crossover Gain: 37.5 dB; Satellite Position: 130°W Longitude Geostationary Orbit

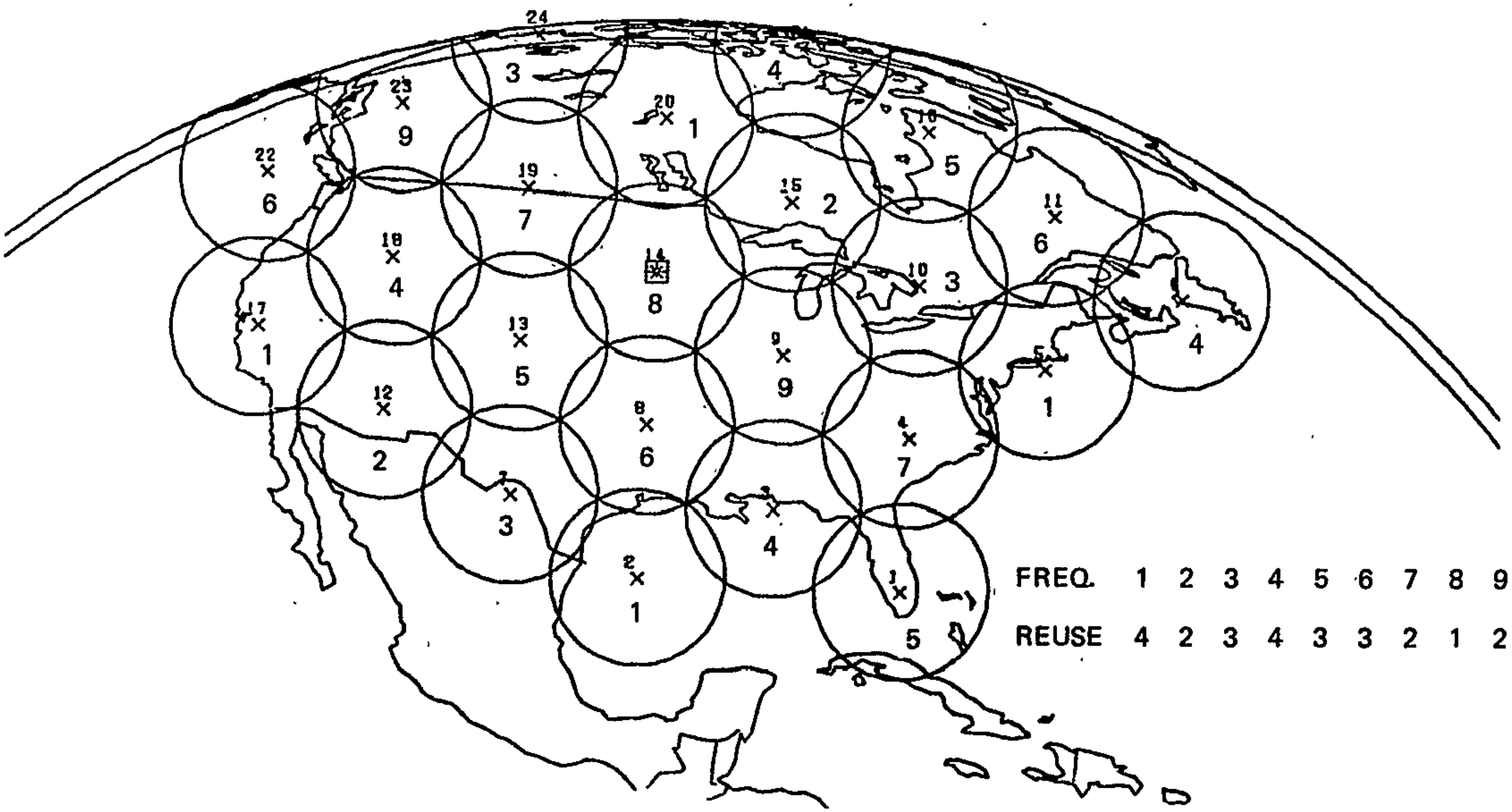
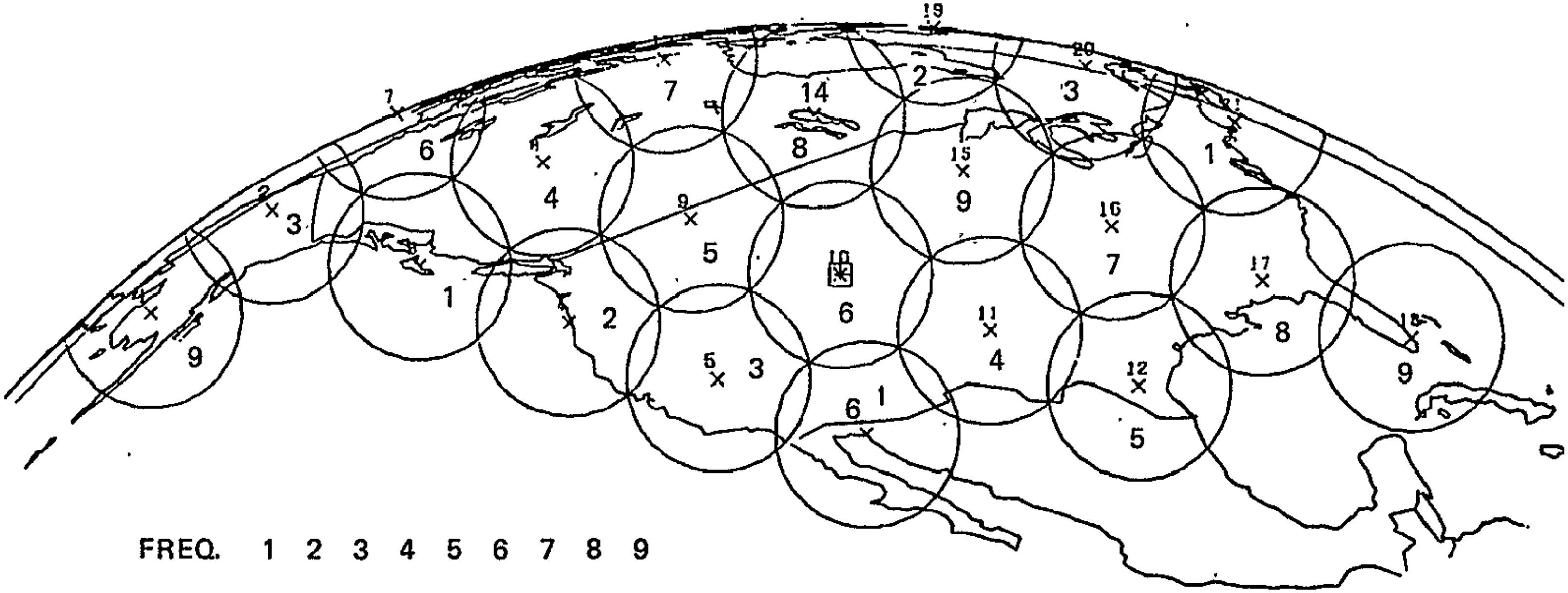


Figure 2-40(a). MSAT-2 Satellite Antenna Beam Layout, 9-Frequency Reuse
Antenna Diameter: 20m; f = 845.5-MHz;Crossover Beamwidth: 1.4°;
Crossover Gain: 37.5 dB;Satellite Position: 90°W Longitude Geostationary Orbit



FREQ.	1	2	3	4	5	6	7	8	9
REUSE	3	2	3	2	2	2	2	2	3

Figure 2-40(b). MSAT-2 Satellite Antenna Beam Layout, 9-Frequency Reuse
Antenna Diameter: 20m; f = 845.5-MHz; Crossover Beamwidth: 1.4°;
Crossover Gain: 37.5 dB; Satellite Position: 130°W Longitude Geostationary Orbit

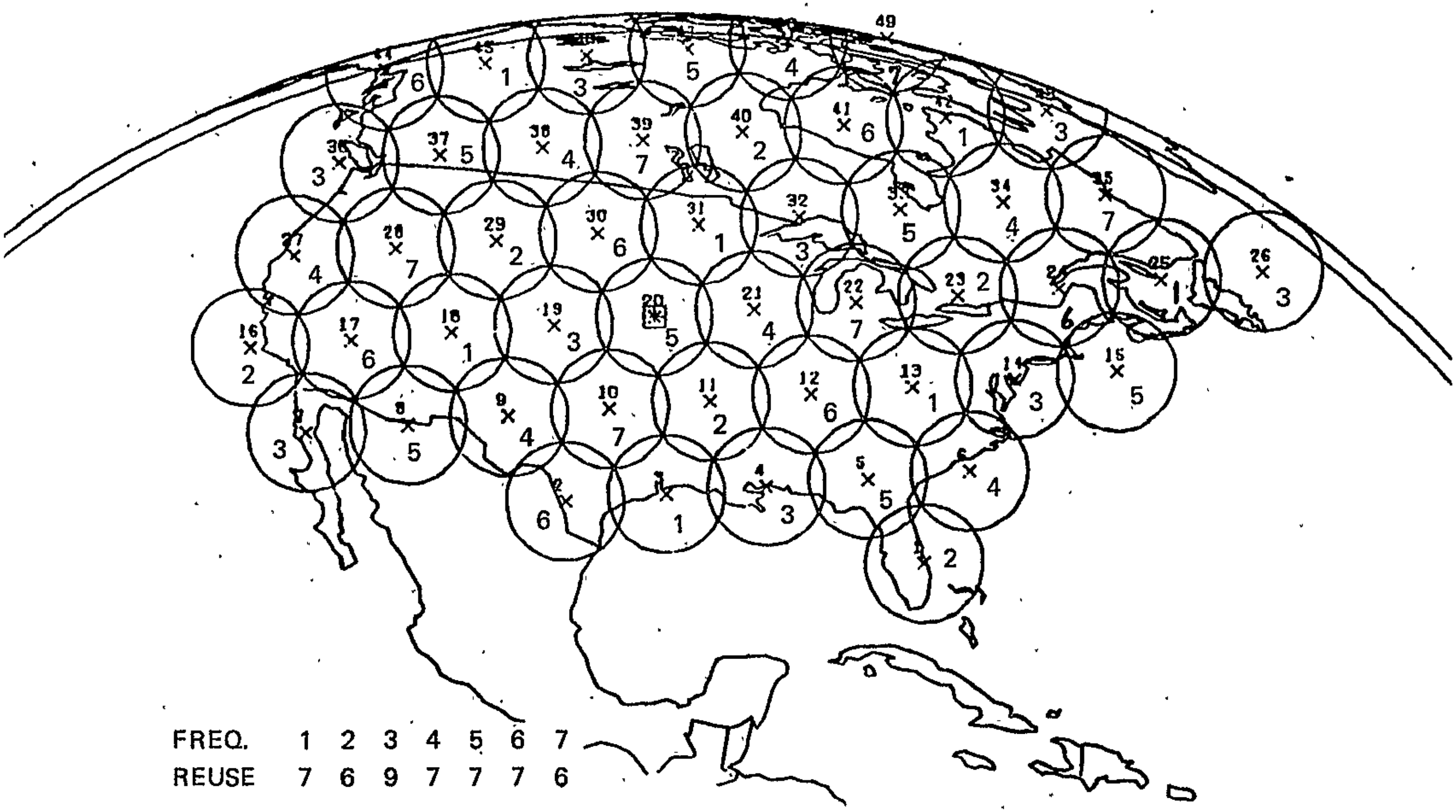
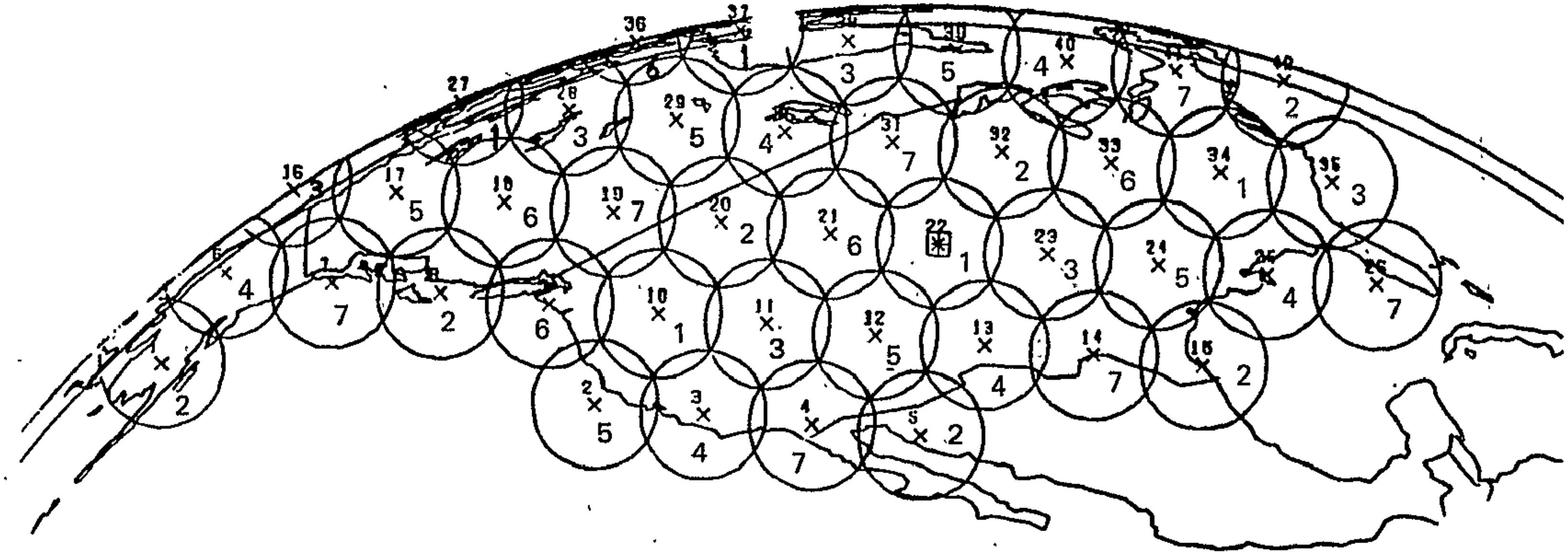
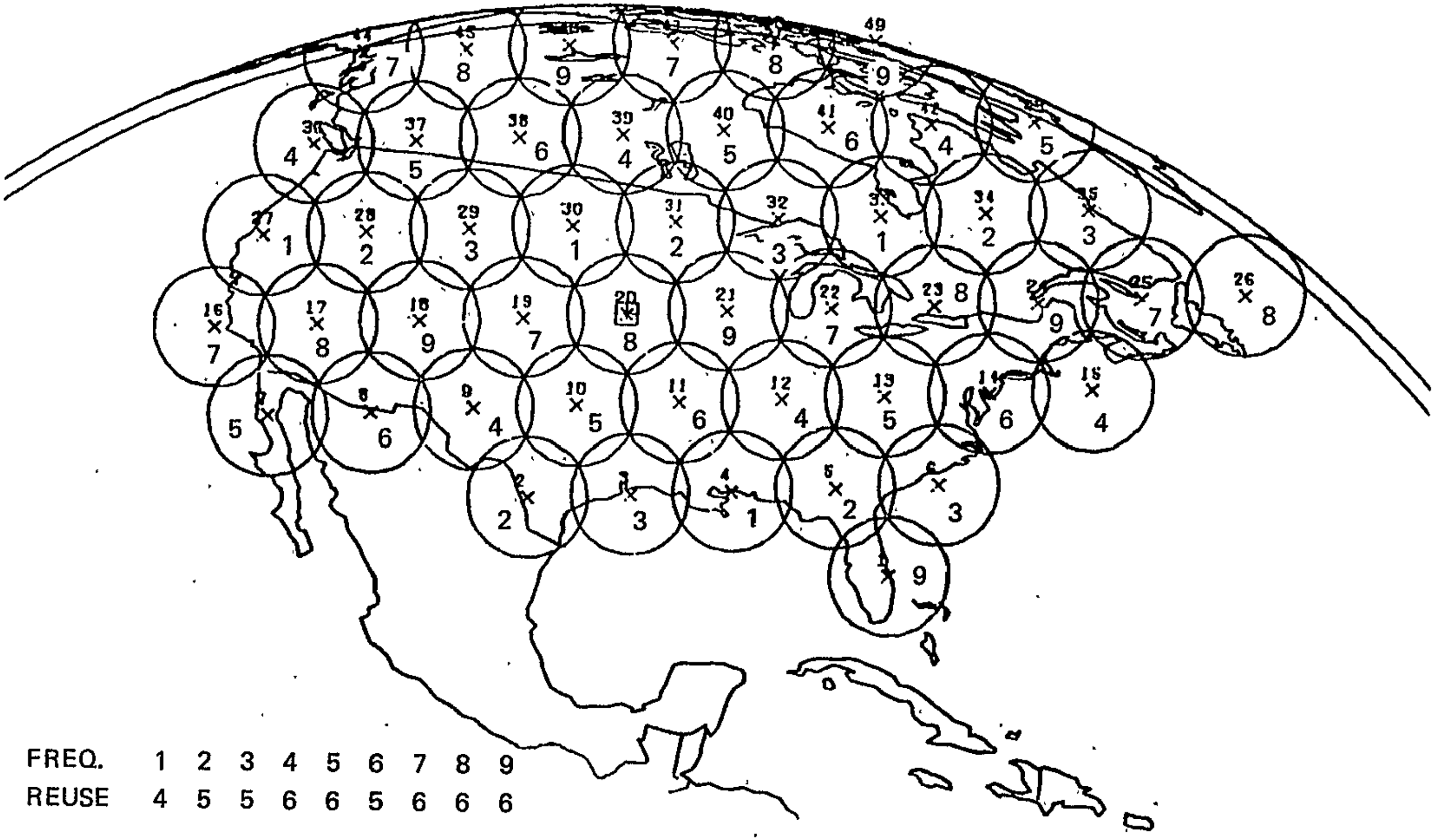


Figure 2-41(a). MSAT-2 Satellite Antenna Beam Layout, 7-Frequency Reuse
Antenna Diameter: 15m; f = 1600 MHz; Crossover Beamwidth: 0.95°;
Crossover Gain: 40.5 dB; Satellite Position: 90°W Longitude Geostationary Orbit



FREQ.	1	2	3	4	5	6	7
REUSE	5	7	6	7	6	4	7

Figure 41(b). MSAT-2 Satellite Antenna Beam Layout 7-Frequency Reuse
Antenna Diameter: 15m; f = 1600 MHz; Crossover Beamwidth: 0.95°;
Crossover Gain: 40.5 dB; Satellite Position: 130°W Longitude Geostationary Orbit



FREQ.	1	2	3	4	5	6	7	8	9
REUSE	4	5	5	6	6	5	6	6	6

Figure 42(a). MSAT-2 Satellite Antenna Beam Layout 9-Frequency Reuse
Antenna Diameter: 15m; f = 1600 MHz; Crossover Beamwidth: 0.95°;
Crossover Gain: 40.5 dB; Satellite Position: 90°W Longitude Geostationary Orbit

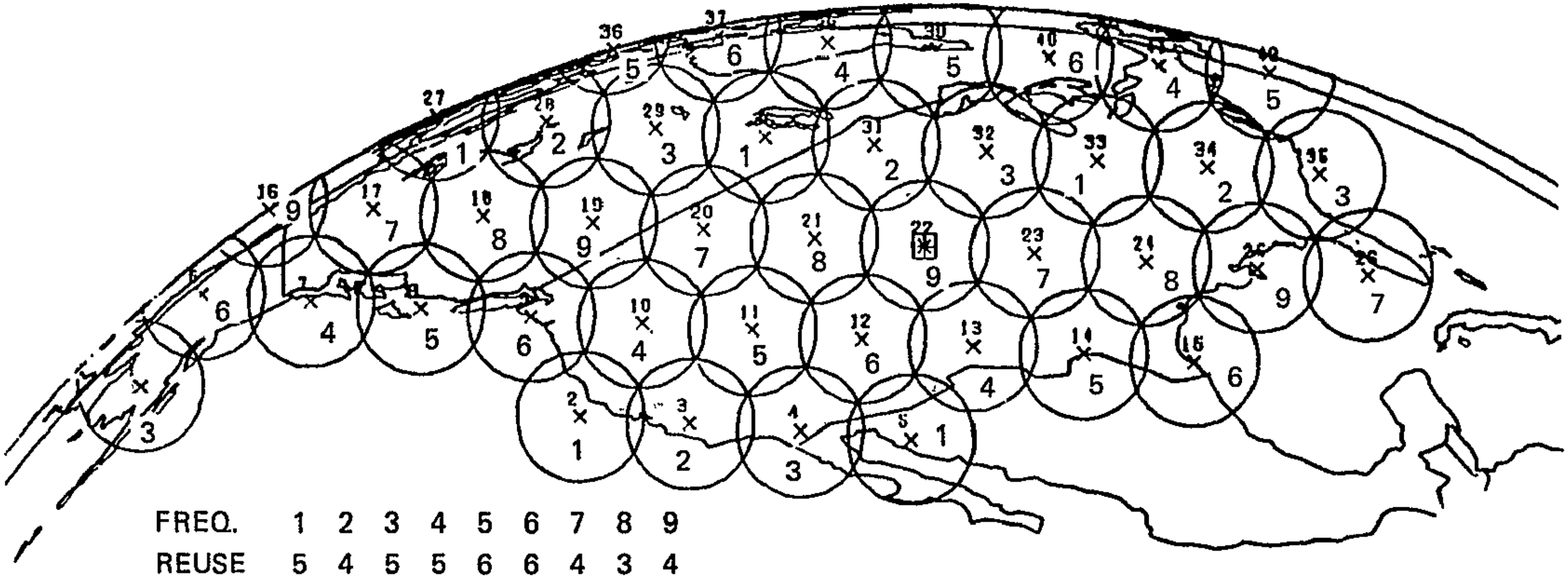
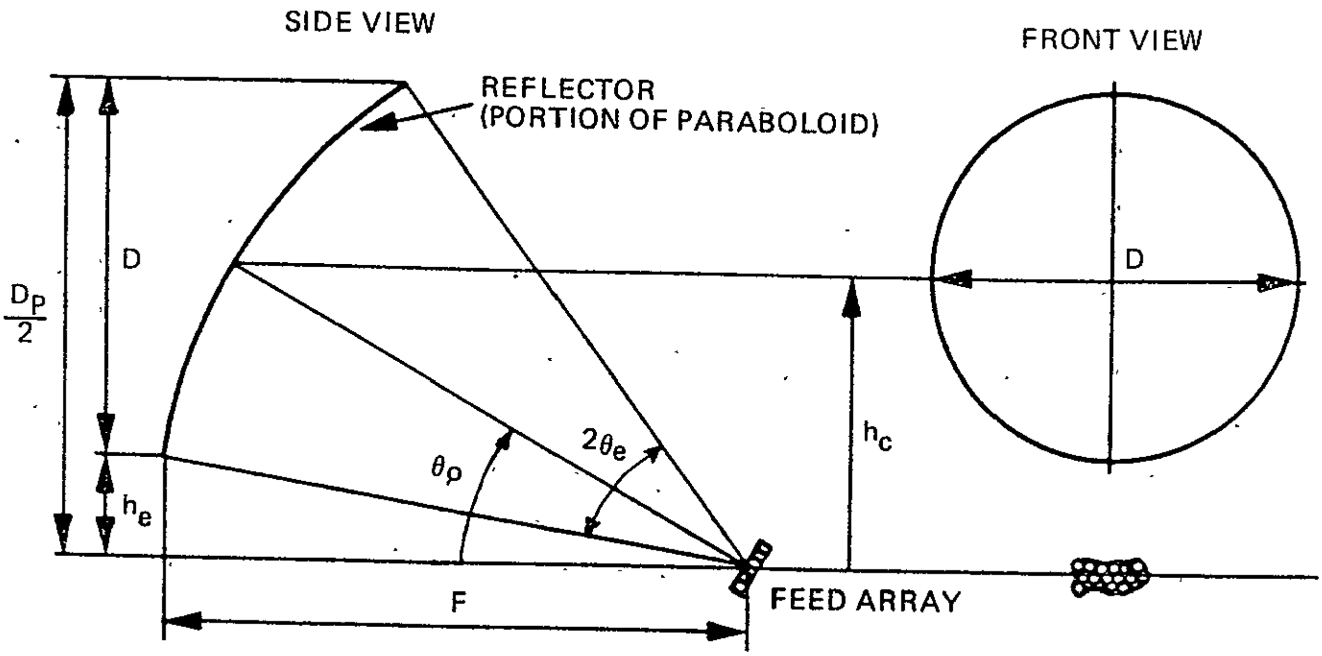
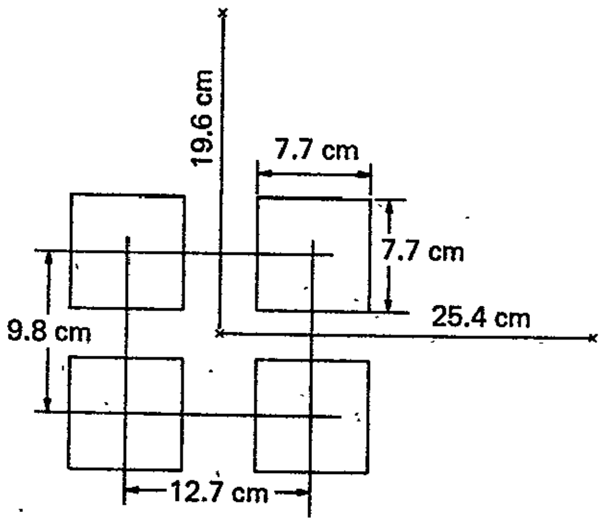


Figure 2-42(b). MSAT-2 Satellite Antenna Beam Layout, 9-Frequency Reuse
Antenna Diamater: 15m; f = 1600 MHz; Crossover Beamwidth: 0.95°;
Crossover Gain: 40.5 dB; Satellite Position: 130°W Longitude Geostationary Orbit



(a) REFLECTOR

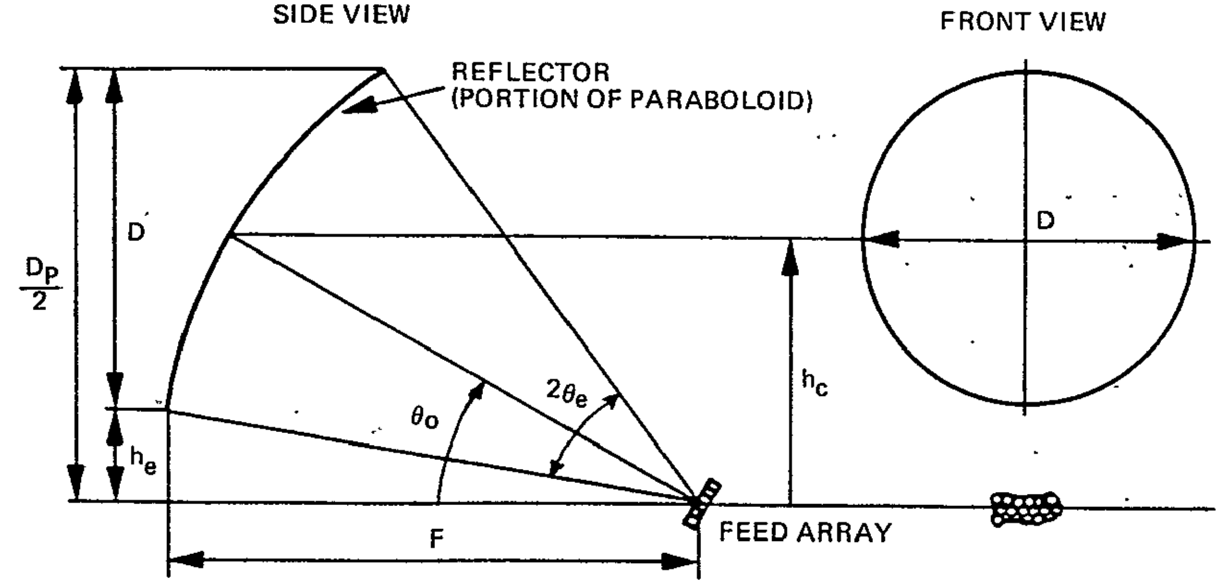
$D = 10.6$ m
$F = 10.6$m, $F/D = 1.0$
$h_e = 1.4$m
$h_c = 6.7$m
$D_p = 24.0$m, $F/D_p = 0.44$
$\theta_o = 35.1^o$
$2\theta_e = 51.46^o$



FREQUENCY: 1600 MHz, WAVELENGTH: 18.75 cm
HONEYCOMB SUBSTRATE – THICKNESS: 1.0 cm
FOR VSWR = 1.5 – DIELECTRIC CONSTANT: 1.17
POLARIZATION: CIRCULAR

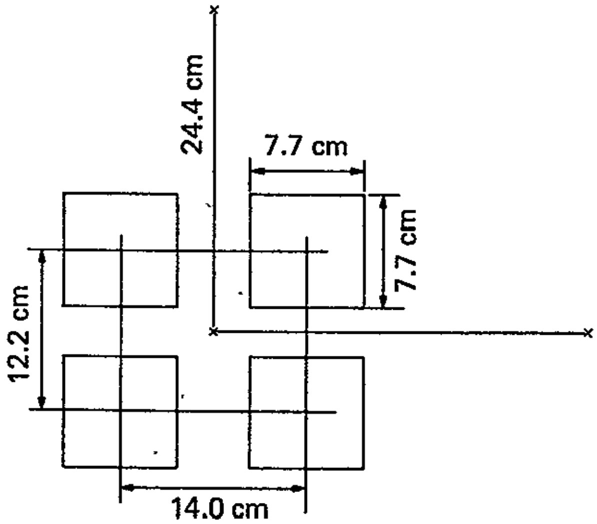
(b) FEED ELEMENT COMPOSED OF MICROSTRIP PATCHES

Figure 2-43. Feed/Reflector Parameters for the 10.6-m L-Band Antenna of MSAT-2



$D = 15.0m$
$F = 18.0m$, $F/D = 1.2$
$h_e = 2.0m$
$h_c = 9.5m$
$D_p = 34.0$, $F/D_p = 0.53$
$\theta_o = 29.56^o$
$2\theta_c = 44.2^o$

(a) REFLECTOR



FREQUENCY: 16.00 MHz, WAVELENGTH: 18.75 cm
HONEYCOMB SUBSTRATE – THICKNESS: 1.0 cm
FOR VSWR = 1.5 – DIELECTRIC CONSTANT: 1.17
POLARIZATION: CIRCULAR

(b) FEED ELEMENT COMPOSED OF MICROSTRIP PATCHES

Figure 2-44. Feed/Reflector Parameters for the 15-m L-Band Antenna of MSAT-2

Table 2-6. Summary Results of Beam Isolation Versus Frequency Reuse and Feed Configuration Study - UHF

ANTENNA	FREQUENCY REUSE FACTOR	FEED CONFIGURATION ELEMENTS (PATCHES/ELEMENT)	TOTAL NUMBER OF ELEMENTS 90°W	130°W	ISOLATION (C/I) dB
15 Meter	1/4	1 (4)	12	12	13
Offset Reflector Antenna		4 (4)	20	21	17
		6 (2)	38	40	20
Surface Tolerance: $<\lambda/50$	1/6	1 (4)	12	12	17
90°W: 12 beams		4 (4)	20	21	23
130°W: 12 beams		6 (2)	38	40	27
	1/7	1 (4)	12	12	23
		4 (4)	20	21	25
		6 (2)	38	40	28
20 Meter	1/4	1 (4)	24	21	12
Offset Reflector Antenna		4 (4)	36	34	15
		6 (2)	68	65	18
	1/5	1 (4)	24	21	14
	1/6	1 (4)	24	81	17
Surface Tolerance: $<\lambda/50$	1/7	1 (4)	24	21	18*
90°W: 24 beams		4 (4)	36	34	21
130°W: 21 beams		6 (2)	68	65	24
	1/9	1 (4)	24	21	22

*Notice that these figures are for the absolute worst case. In Section 3-5, it is shown that 20 dB is achievable for most situations.

Table 2-7. Summary Results of Beam Isolation Versus Frequency Reuse and Feed Configuration Study - L-Band

Offset Reflector Antenna Diameter	FREQUENCY REUSE FACTOR	FEED ELEMENTS (PATCHES/ELEMENT)	TOTAL NUMBER OF BEAMS (ELEMENTS) 90°W	130°W	ISOLATION dB
10.6 m	1/9	1 (4)	24 (24)	21 (21)	22
15 m	1/7	1 (4)	49 (49)	42 (42)	15
	1/7	4 (4)	49 (72)	42 (67)	17
	1/7	6 (2)	49 (128)	42 (115)	20
	1/9	1 (4)	49 (49)	42 (42)	19
	1/9	4 (4)	49 (72)	42 (67)	21
	1/9	6 (2)	49 (128)	42 (115)	23

C-3

correlation diameters of between 1/10th to 1/20th of the reflector diameter. For RMS errors of the order of 1/40th of the wavelength the isolation figures may be reduced by approximately 1 dB.

2.8 SELECTION OF ANTENNA SIZE AND FEED CONFIGURATION

The discussion in Section 2.7 has narrowed down the possible feed configurations. The final feed design cannot be determined without considering the antenna size. Both the antenna size and the feed design will be determined in this section, although many of the factors that must be considered in the selection process are not addressed here in detail.

In order to properly size the antenna and determine the feed design for the baseline system, various combinations of antenna size, feed design, and the frequency reuse factor are tabulated in Table 2-8. There are sixteen combinations or options listed in the Table. These combinations are composed of three antenna sizes, three frequency reuse factors, and three feed designs. (It is noted that the 9-frequency reuse is not included in the table because of its limited reuse of the available spectrum.) The antenna sizes are 15, 20, and 25 meters. The feed designs are 1-element or nonoverlapping feed, 4-element, and 6-element designs. The following procedures will be used to size the antenna and to select the feed design:

1) Estimate the payload weight using the model in Appendix D.

2) Estimate the payload power.

3) Calculate the number of channels that can be powered up by taking into consideration the interbeam isolation and the overall C/I as described in Appendix E.

4) Calculate the number of channels that can be supported by the available bandwidth.

Table 2-8. Various Combinations of Antenna Sizes, Feed Designs, and Frequency Reuse Factors

ANT SIZE (m)	NO. OF BEAMS	FREQUENCY REUSE SCHEME	NO. OF ELEMENTS PER BEAM	TOTAL NO. OF ELEMENTS	ANTENNA ISOLATION (dB)	NO. OF POTENTIAL CHANNELS	OPTIONS
15	12	7	1 4 6*	12 20(21)** 38(40)	23 25 28	3428	1 2 3
		6	1 4 6*	12 20(21) 38(40)	17 23 27	4000	4 5 6
		4	1 4 6*	12 20(21) 38(40)	13 17 20	6000	7 8 9
20	24 (21)	7	1 4 6*	24(21) 36(34) 68(65)	20 21 24	6857 (6000)	10 11 12
		4	1 4 6*	24(21) 36(34) 68(65)	12 15 18	12000 (10500)	13 14 15
25	34	7	1	34	-	9714	16

NOTES:

**When a pair of numbers is given, the parenthesized one is for the 130° W satellite and the other for the 90° W satellite.

*The 6-element designs require only 2 micropatches per element while the other designs utilize 4 patches per element.

5) Determine the number of actual satellite channels that will be available by comparing the number of channels established in Step 3 and Step 4. If, for a given design, the number of channels obtained in Step 3 is larger than that in Step 4, then the capacity of this system will be limited by the available frequency band and there will be excessive spacecraft power not being utilized.
6) Assess the relative system costs or user costs.

2.8.1 Estimated Payload Weight

The antenna size and feed design affect the payload weight in two ways. First, a larger antenna weighs more because of the larger reflector and the longer supporting boom. Secondly a larger antenna produces a smaller beam which means more beams will be required to cover the same service area. More beams means a heavier feed assembly and ultimately increases the payload weight. Because the payload weight depends highly on the choice of the antenna size and the feed design, it is, therefore, imperative to consider the effects on the payload weight before the selection of antenna diameter can be made.

The payload weight for the various options listed in Table 2-8 has been estimated by determining the weight of the UHF feed assembly, the antenna, and the transponder, using the model developed in Appendix D.

The estimated payload weights of the various options are shown in Table 2-9. It is obvious from the Table that the weight of some payloads exceeds the projected capability of the baseline bus. These options will therefore be eliminated from further examinations (options 11, 12, 14, 15, and 16).

2.8.2 Available Payload Power

The DC power available to the payload can be obtained from Figure 2-7 once the payload weight is known. The DC power, for options that have not been eliminated by Step 1, is given in Table 2-9.

2.8.3 The Number of Channels That Can Be Powered Up

The number of channels that can be supported by the spacecraft power subsystem can be calculated for each option by dividing the available RF power by the required power per channel. The available RF power can be approximated by multiplying the available payload power given in Table 2-9 by the overall DC-to-RF conversion efficiency, which is assumed to be 26%.

The required power per channel is the power needed to yield a net end-to-end EB/NO of 12.7 dB, which is 2 dB above the minimum value required to satisfy the bit-error rate performance requirement (Chapter 3). The net EB/NO is the equivalent EB/NO after properly accounting for both the noise and interference degradations.

For a given link performance, the required power varies as a function of both the overall C/I and the modes of communications. In order to estimate the per-channel power, it is necessary to first determine the overall C/I, which is a function of the interbeam isolation, intermod level, multipath, etc., as described in Appendix E. Based on the analysis presented in the Appendix, the overall C/I

Table 2-9. Estimated Payload Weights and Payload Power

	ESTIMATED WEIGHTS, kg (1)						
OPTIONS	1, 4, 7	2, 5, 8	3, 6, 9	10, 13	11, 14	12, 15	16
UHF FEED ASSEMBLY	128	206(215)	361(379)	256(224)	374(351)	649(618)	363
TRANSCEIVER	15	15	15	17	17	17	20
UHF REFLECTOR AND[2] SUPPORTING STRUCTURE	174	174	174	209	209	209	270
Ku-BAND REFLECTOR	4	4	4	4	4	4	4
Ku-BAND TWT	4	4	4	4	4	4	4
TOTAL WEIGHT	325	403(412)	558(576)	490(458)	608(585)	883(852)	661
PAYLOAD POWER (WATTS) (MSAT-2 BASELINE)	2880	2160(2080)	740(570)	1360(1660)	-	-	-

(1) When a pair of numbers is given, the parenthesized one is for the 130° W satellite while the other is for the 90° W satellite.

(2) Including a contingency of 16 to 20%.

has been calculated and shown in Table 2-10 for the options being considered. As indicated in the table, the overall C/I for the mobile-to-mobile communications is, in general, lower than that for the fixed-station-to-mobile communications. As a result, the power required for mobile-to-mobile communications will be higher than that for the fixed-station-to-mobile communications.

With the overall C/I known, the per-channel power can be readily determined. As an example, two link budgets are shown in Tables 3-11 and 3-12 for the mobile-to-mobile and fixed-station-to-mobile communications, using an overall C/I of 20 dB. The power required is -10.58 dBW, or 0.088 watts, and -10.62 dBW, or 0.087 watts, for the mobile-to-mobile and fixed-station-to-mobile communications, respectively. The per-channel power for the various options under consideration has been determined by substituting the appropriate interference parameters into the link tables in Tables 2-11 and 2-12. The resulting per-channel power is shown in Tables 2-13 and 2-14 (column 10). It is noted that the per-channel power is not provided for options which have a C/I of 10 dB or less. Although it may be possible to compensate for the low C/I by increasing the power per channel, the additional power would be tremendous. Consequently, a C/I of less than 10 dB is considered unacceptable.

With the per-channel power known, the number of satellite channels that can be supported by the available power has been determined and shown in Tables 2-13 and 2-14 (column 11) for the east satellite. The available RF power for the east satellite is shown in column 9.

2.8.4 The Number of Channels Supported by the Available Frequency Band

The number of channels that is available for a given bandwidth is determined by the frequency reuse factor, channel spacing, and the number of multiple beams, as indicated by the formula given in Section 2.2.1. Using a 10-MHz bandwidth

Table 2-10. Overall C/I

Options	Sidelobe Levels, dB	Overall C/I, dB	
		Mobile-to-Mobile	Fixed-to-Mobile
1	23	15.3	18.5
2	25	16.5	19.2
3	28	18.1	19.8
4	17	10.4	15.4
5	23	15.3	18.5
6	27	17.6	19.6
7	13	6.6	12.3
8	17	10.4	15.4
9	20	13.0	17.2
10	20	13.0	17.2
11	21	13.8	17.7
12	24	15.9	18.9
13	12	5.7	11.4
14	15	8.5	13.9
15	18	11.3	16.0
16(1)	-	-	-

(1) No C/I values are given for option 16 because its payload is too heavy.

TABLE 2-11. DESIGN CONTROL TABLE FOR MOBILE-TO-MOBILE LINKS (AN EXAMPLE)

		MOBILE TO SAT					SAT TO MOBILE				
	PDF	DESIGN	FAV TOL	ADV TOL	MEAN	VAR (X.01)	DESIGN	FAV TOL	ADV TOL	MEAN	VAR (X.01)
TRANSMITTER PARAMETERS	---										
1)XMIT POWER,DBW	TRI	7.00	1.00	0.00	7.33	5.56	-10.58	.50	.50	-10.58	4.17
2)XMIT CIRCUIT LOSS,DB	REC	-1.50	.20	.50	-1.65	4.08	-2.40	.20	1.00	-2.80	12.00
3)ANTENNA GAIN,DBI	TRI	10.00	1.50	0.00	10.50	12.50	42.20	.50	.50	42.20	4.17
4)EIRP,DBW ((1)+(2)+(3))		15.50			16.18		29.22			28.82	
5)POINTING LOSS,DB	TRI	0.00	0.00	0.00	0.00	0.00	-1.00	.30	.50	-1.07	2.72
PATH PARAMETERS											
6)SPACE LOSS,DB		-182.94			-182.94		-183.24			-183.24	
(FREQUENCY,MHZ =		836.00					866.00				)
(RANG= 40000 KM)											
7)ATMOSPHERIC ATTN,DB	TRI	0.00	0.00	.10	-.03	.06	0.00	0.00	.10	-.03	.06
8)E.O.B.LOSS,DB	TRI	-4.00	0.00	.50	-4.17	1.39	-4.00	0.00	.50	-4.17	1.39
9)MULTIPATH LOSS,DB	GAU	-5.00	2.00	0.00	-4.00	11.11	-5.00	2.00	0.00	-4.00	11.11
10)SHADOWING LOSS,DB	DEL	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	
RECEIVER PARAMETERS											
11)POLARIZATION LOSS,DB	TRI	-.50	.10	.10	-.50	.17	-.50	.10	.10	-.50	.17
12)ANTENNA GAIN,DBI	TRI	41.60	.50	.50	41.60	4.17	10.00	1.50	0.00	10.50	12.50
13)POINTING LOSS,DB	TRI	-1.00	.30	.50	-1.07	2.72	0.00	0.00	0.00	0.00	0.00
14)RECEIVED SIGNAL POWER,DBW		-136.34			-134.92		-154.52			-153.69	
(SUM OF LINES 4 - 13)											
15)SYSTEM TEMPERATURE,DBK	GAU	29.22	.90	1.30			27.06	.20	.40		
(CIRCUIT LOSS,DB =		-2.40	.20	1.00			-1.50	.20	.20		)
(RCVR N.F. ,DB =		2.20	.70	.30			1.50	0.00	.20		)
(ANTENNA TEMP,K =		290.00	0.00	0.00			220.00	0.00	0.00		)
16)RECEIVED No,DBW/HZ	GAU	-199.38	.90	1.30	-199.58	13.44	-201.54	.20	.40	-201.64	1.00
((15)-228.6 DBW/HZ)											
(BANDWIDTH,KHZ =		5.00					5.00				)
CHANNEL PERFORMANCE											
17)RCVD C/NO,DB-HZ ((14)-(16))		63.04			64.66		47.01			47.95	
18)EFFECTIVE C/NO,DB-HZ		62.64			64.09		46.50			47.36	
(OVERALL C/I,DB =	GAU						20.00	.74	.76	20.00	6.24)
(INTERBEAM ISOLATION =	TRI	36.20	1.00	1.00	36.20	16.67	36.20	1.00	1.00	36.20	)
(INTERSAT. ISOLATION =							23.00	.50	.50	23.00	)
(INTERMOD ISOLATION =							24.00	1.00	1.00	24.00	)
(TURNAROUND C/NO =	GAU						63.04			64.66	55.19)
(NO(UP)/NO(REQUIRED) =		.15					.15				)
(MODEM LOSS,DB =		0.00			0.00		0.00			0.00	)
19)REQUIRED C/NO,DB-HZ		52.74			52.74		44.50			44.50	
20)PERFORMANCE MARGIN,DB		9.90			11.35	.85	2.00			2.86	1.05
((18)-(19))						(1 SIG)					(1 SIG)

TABLE 2-12. DESIGN CONTROL TABLE FOR FIXED-STATION-TO-MOBILE (FORWARD) LINKS (AN EXAMPLE)

		GATEWAY TO SAT					SAT TO MOBILE				
	PDF	DESIGN	FAV TOL	ADV TOL	MEAN	VAR (X.01)	DESIGN	FAV TOL	ADV TOL	MEAN	VAR (X.01)
TRANSMITTER PARAMETERS	---										
1)XMIT POWER,DBW	TRI	-1.07	1.00	.50	-.90	9.72	-10.62	.50	.50	-10.62	4.17
2)XMIT CIRCUIT LOSS,DB	REC	-2.00	.50	.50	-2.00	8.33	-2.40	.20	1.00	-2.80	12.00
3)ANTENNA GAIN,DBI	TRI	49.60	1.00	1.00	49.60	16.67	42.20	.50	.50	42.20	4.17
4)EIRP,DBW ((1)+(2)+(3))		46.53			46.70		29.18			28.78	
5)POINTING LOSS,DB	TRI	-.50	0.00	.50	-.67	1.39	-1.00	.30	.50	-1.07	2.72
PATH PARAMETERS											
6)SPACE LOSS,DB		-206.90			-206.90		-183.24			-183.24	
(FREQUENCY,GHZ/MHZ =		13.20					866.00				)
(RANG= 40000 KM)											
7)ATMOSPHERIC ATTN,DB	TRI	-1.10	.10	.10	-1.10	.17	0.00	0.00	.10	-.03	.06
8)E.O.B.LOSS,DB	TRI	-4.00	0.00	.50	-4.17	1.39	-4.00	0.00	.50	-4.17	1.39
9)MULTIPATH LOSS,DB	GAU	0.00	0.00	0.00	0.00	0.00	-5.00	2.00	0.00	-4.00	11.11
10)SHADOWING LOSS,DB	DEL	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	
RECEIVER PARAMETERS											
11)POLARIZATION LOSS,DB	TRI	0.00	0.00	.10	-.03	.06	-.50	.10	.10	-.50	.17
12)ANTENNA GAIN,DBI	TRI	32.30	.50	.50	32.30	4.17	10.00	1.50	0.00	10.50	12.50
13)POINTING LOSS,DB	TRI	-.50	.20	.20	-.50	.67	0.00	0.00	0.00	0.00	0.00
14)RECEIVED SIGNAL POWER,DBW		-134.17			-134.37		-154.56			-153.73	
(SUM OF LINES 4 - 13)											
15)SYSTEM TEMPERATURE,DBK	GAU	29.12	.60	.90			27.06	.20	.40		
(CIRCUIT LOSS,DB =		-1.50	.10	.40			-1.50	.20	.20		)
(RCVR N.F. ,DB =		3.00	.50	.50			1.50	0.00	.20		)
(ANTENNA TEMP,K =		290.00	0.00	0.00			220.00	0.00	0.00		)
16)RECEIVED NO,DBW/HZ	GAU	-199.48	.60	.90	-199.63	6.25	-201.54	.20	.40	-201.64	1.00
((15)-228.6 DBW/HZ)											
(BANDWIDTH,KHZ =		5.00					5.00				)
CHANNEL PERFORMANCE											
17)RCVD C/NO,DB-HZ ((14)-(16))		65.30			65.25		46.97			47.91	
18)EFFECTIVE C/NO,DB-HZ		63.05	.38	.43	63.03		46.50			47.33	
(OVERALL C/I,DB =	GAU						20.00	.74	.76	20.00	6.24)
(INTERBEAM ISOLATION =							30.00	1.00	1.00	30.00	)
(INTERSAT. ISOLATION =							23.00	.50	.50	23.00	)
(INTERMOD ISOLATION =	TRI	30.00	1.00	1.00	30.00	16.67	24.00	1.00	1.00	24.00	)
(TURNAROUND C/NO =	GAU						65.30			65.25	48.81)
(NO(UP)/NO(REQUIRED) =		.05					.05				)
(MODEM LOSS,DB =		0.00			0.00		0.00			0.00	)
19)REQUIRED C/NO,DB-HZ		57.51			57.51		44.50			44.50	
		--------			--------	------	------			------	-----
20)PERFORMANCE MARGIN,DB		5.54			5.51	.81	2.00			2.83	1.02
((18)-(19))						(1 SIG)					(1 SIG)

Table 2-13. Summary of Payload Weights, Antenna Isolation, Overall C/I, Available Power, and the Number of Satellite Channels (Mobile-to-Mobile)

Options	Ant. Size (m)	Freq. Reuse Factor	No. of Elements Per Beam	Antenna Isolation (dB)	Overall C/I (dB)	Payload Weight (kg)	Available DC Power (watts)	Available RF Power watts	Power Per Channel (watts)	No. of Channels That Can Be Powered Up	No. of Channels that can be Supported by the Available Bandwidth	No. of Actual Channels Per Satellite East	West
1	15	7	1	23	15.3	325	2880	749	0.19	3942	3428	3428	3428
2	15	7	4	25	16.5	403	2160	562	0.17	3284	3428	3284	3159
3	15	7	6	28	18.1	558	740	192	0.16	1210	3428	1210	932
4	15	6	1	17	10.4	325	2880	749	0.75	998	4000	998	998
5	15	6	4	23	15.3	403	2160	562	0.19	3114	4000	3114	2995
6	15	6	6	27	17.6	558	740	192	0.16	1175	4000	1175	906
7	15	4	1	13	6.6	325	2880	749	-	-	6000	-	-
8	15	4	4	17	10.4	403	2160	562	0.75	749	6000	749	720
9	15	4	6	20	13.0	558	740	192	0.23	833	6000	833	641
10	20	7	1	20	13.0	490	1360	354	0.13	2733	6857	2733	3335
11	20	7	4	21	13.8	608	-	-	-	-	6857	-	-
12	20	7	6	24	15.9	883	-	-	-	-	6857	-	-
13	20	4	1	12	5.7	490	1360	354	-	-	12000	-	-
14	20	4	4	15	8.5	608	-	-	-	-	12000	-	-
15	20	4	6	18	11.3	883	-	-	-	-	12000	-	-
16	25	7	1	-	-	661	-	-	-	-	9714	-	-

ORIGINAL PAGE IS OF POOR QUALITY

Table 2-14. Summary of Payload Weights, Antenna Isolation, Overall C/I, Available Power, and the Number of Satellite Channels (Fixed-Station-to-Mobile)

Options	Ant. Size (m)	Freq. Reuse Factor	No. of Elements Per Beam	Antenna Isolation (dB)	Overall C/I (dB)	Payload Weight (kg)	Available DC Power (watts)	Available RF Power (watts)	Power Per Channel (watts)	Channels That Can Be Powered Up	No. of Channels That Can Be Supported by the Available Bandwidth	No. of Actual Channels Per Satellite: East	No. of Actual Channels Per Satellite: West
1	15	7	1	23	18.5	325	2880	749	0.16	4859	3428	3428	3428
2	15	7	4	25	19.2	403	2160	562	0.16	3646	3428	3428	3428
3	15	7	6	28	19.8	558	740	192	0.15	1245	3428	1245	958
4	15	6	1	17	15.4	325	2880	749	0.19	4225	4000	4000	4000
5	15	6	4	23	18.5	403	2160	562	0.16	3646	4000	3646	3507
6	15	6	6	27	19.6	558	740	192	0.15	1245	4000	1245	958
7	15	4	1	13	12.3	325	2880	749	0.31	2416	6000	2416	2416
8	15	4	4	17	15.4	403	2160	562	0.19	3170	6000	3170	3049
9	15	4	6	20	17.2	558	740	192	0.16	1186	6000	1186	913
10	20	7	1	20	17.2	490	1360	354	0.09	3888	6857	3888	4745
11	20	7	4	21	17.7	608	-	-	-	-	6857	-	-
12	20	7	6	24	18.9	883	-	-	-	-	6857	-	-
13	20	4	1	12	11.4	490	1360	354	0.23	1539	12000	1539	1873
14	20	4	4	15	13.9	608	-	-	-	-	12000	-	-
15	20	4	6	18	16.0	883	-	-	-	-	12000	-	-
16	25	7	1	-	-	661	-	-	-	-	9714	-	-

and a 5-kHz channel spacing, the number of available channels has been calculated for the east and west satellites for various frequency reuse factors considered. As indicated in Tables 2-13 and 2-14, the number of channels ranges from 3,400 to 12,000, depending on the frequency reuse scheme and the number of beams.

2.8.5 The Number of Actual Satellite Channels

The number of actual satellite channels is equal to the smaller of the number of channels that can be supported by the available frequency band (Column 12 in Tables 2-13 and 2-14) and those that can be supported by the available power. Among all the options considered, the number of usable channels or actual channels, for some, is limited by the available frequency band and for others by the available power. The number of actual channels is shown in Tables 2-13 and 2-14 (columns 13 and 14) for both the 90° W and 130° W satellites.

The numbers of channels in Tables 2-13 and 2-14 are for a hypothetical situation when all the traffic is either mobile-to-mobile or fixed-station-to-mobile. In reality, this obviously is not the case. The number of channels thus must be modified. In order to determine the number of actual channels, it is necessary to know the amount of mobile-to-mobile communications relative to the total amount of traffic. Based on [3], mobile-to-mobile traffic accounts for about 25% of all the mobile radio service and only 5% of the mobile telephone and data services. For MSAT-2, it is assumed that mobile-to-mobile traffic will account for 10% of the total traffic. Based on this assumption, the number of satellite channels has been recalculated and is shown in Table 2-15 for all options except options 3, 6, 7, 9, and 11 through

Table 2-15.

Number of Satellite Channels for Combined Mobile-to-Mobile and Fixed-Station-to-Mobile Operations

Options	Antenna Size, m	No. of Elements Per Beam	Per-Channel Power, Watts	Number of Channels East	West	Total	Comments
1	15	1	0.16	3428	3428	6856	Frequency limited.
2	15	4	0.16	3428	3428	6856	Frequency limited.
4	15	1	0.25	3050	3050	6105	
5	15	4	0.16	3473	3344	6817	
8	15	1	0.25	2248	2160	4408	
10	20	1	0.09	3726	4547	8273	

16. Shown in the table is the capacity of the east satellite, the west satellite, and the total capacity. Options 3, 6, and 9 have been eliminated because the resulting satellite channels are substantially less than other options having the same antenna size and frequency reuse factor. Options 11, 12, 14, 15, and 16 are too heavy for the baseline bus. Options 7 and 13 have been eliminated because of low overall C/I values, ranging from 5.7 to 6.7 dB for mobile-to-mobile communications and from 11.6 to 12.5 dB for fixed-station-to-mobile communications.

The 6-element feed designs and the 25-meter design have, by now, been eliminated.

2.8.6 System Costs or User Costs

For the purpose of the tradeoff analysis it suffices to estimate only the relative costs. As previously mentioned, the user cost is a good measure of the financial health of the system because all costs will eventually be borne by the end users. The calculation of the user cost, however, is very complicated and involves the cost of various ground equipment, inflation rate, investment return, etc. To further simplify the analysis, only the satellite cost, and consequently the user cost, will be treated as variables while holding constant all other costs and assumptions.

The user cost is generally inversely proportional to the number of satellite channels and directly proportional to the complexity of the transponder for a fixed antenna size, under the assumption that all channels will be fully utilized. For a given antenna size, the complexity of the transponder depends on the antenna feed design. There are three feed designs that have been considered: 1-element, 4-element, and 6-element. The 1-element, or the nonoverlapping feed, is the simplest design and will result in the lowest user cost. Even though a higher interbeam isolation can be obtained by using an overlapping feed, the overlapping feed designs increase the user cost in two ways. First, the transponder, including the feed, is more complex for an over-lapping feed design, increasing the hardware cost and subsequently the user cost. Secondly, the transponder is also heavier, in addition to being more complex. A heavier payload means fewer satellite channels, which in turn further increases the user cost.

Of the 16 options in Table 2-8, ten have been eliminated for various reasons. The remaining six options are tabulated in Table 2-15. Of these, four

utilize a single feed design and two utilize a 4-element, overlapping feed design.

Among the 15-m antenna designs, options 4 and 8 have far less channels than others, and hence can be eliminated. The rest of the 15-m designs, i.e., options 1, 2, and 5, roughly have the same channel capacity, and the resulting user cost should therefore be approximately the same. Compared to option 10, which utilizes a 20-m antenna, there is, however, a significant difference in the channel capacity between the 15-m and the 20-m designs. In terms of the satellite cost, the 15-m satellite would be less costly than the 20-m system due to a smaller antenna and less electronics. Based on data obtained from [14], the cost difference between a 15-m and 20-m system, consisting of two active satellites and one in-orbit spare, is roughly 38 million dollars including launch costs. However, compared to the cost of the space segment which is in the range of 500 million dollars, the cost difference between the two systems is relatively insignificant. Because the 20-m design can provide a substantial number of additional channels, the end user cost may even be lower.

In addition, there is one advantage that the 20-m design has over the 15-m designs. As indicated in Tables 2-14 and 2-15, the capacity of the 15-m systems are either limited or close to being limited by frequency, even for a 10-MHz allocation. If a narrower band is allocated, the capacity will be even more severely limited. This will deprive the system of any benefits from future technology improvements, such as more efficient power amplifiers, a more power-efficient modulation, etc. On the other hand, the 20-m system provides ample room for further enhancement.

Considering both the cost effects and the channel performance, the 20-m, single feed design is selected as the baseline system design.

2.9 OVERALL C/I, INTERSATELLITE ISOLATION, AND INTERMOD ISOLATION

In a mobile satellite system that utilizes multiple beams and frequency reuse, cochannel interference is a major problem that must be solved. Interference arises from many sources, including intermodulation products, turnaround interference, adjacent or intersatellite interference, and interbeam interference. This problem is exacerbated by the presence of multipath fading. The existence of multiple interference sources to a certain extent makes the mobile satellite system an interference-limited system. To maintain an acceptable performance, stringent requirements on antenna sidelobes, intermodulation products, etc., are often necessary. These requirements, however, increase the complexity of the system and utlimately reduce its capacity. In the 55-m study, the required overall C/I is 17 dB, which is the same as that established for the AMPS (Advanced Mobile Telephone Service). To meet the 17-dB requirement, the antenna sidelobe level is kept at 27 dB below the main beam using a complicated and heavy overlapping feed design. In the previous section, a single feed design was chosen for MSAT-2 because of its simplicity and light weight. The achievable interbeam isolation for a 7-frequency reuse scheme, however, is only about 20 dB. Can MSAT-2 operate at a lower C/I than AMPS and the 55-m systems? Should a more stringent requirement be placed on the antenna sidelobe level, the intermod level, etc., in order to improve the overall C/I? These questions will be addressed in the following section.

2.9.1 Justification for the 17-dB C/I Requirement Established for AMPS

The 17-dB C/I requirement for AMPS is established for an analog voice (narrowband FM) transmission. It is based on a subjective test performed by Bell Laboratory.

Results of the test indicate that a good to excellent voice quality is obtained at a C/I of 17 dB and a C/N of 18 dB.

The 55-m system also employs narrowband FM voice. Consequently, the 17-dB requirement was adopted due to the lack of other data. Since the 55-m study, more data has become available. A recent investigation using the Land Mobile Satellite Service Channel Simulator has demonstrated that the required C/I can be reduced by increasing the transmitted power or the line-of-sight carrier-to-noise ratio [C/N] [15]. A plot of the required C/N as a function of the C/I obtained from [15] is shown in Figure 2-45 for a Rician fading environment with the propagation SNR and the normalized RMS frequency deviation as a parameter. The propagation SNR is the line-of-sight carrier-to-multipath ratio and is denoted by C/MF in the figure. The RMS frequency deviation shown is normalized to the noise bandwidth of the receiver baseband filter. Figure 2-46 is a similar plot for the Rayleigh fading environment. Both figures clearly indicate that the 17-dB C/I is not an absolute minimum. Operating in a lower C/I environment is possible if the degradation caused by the interference can be compensated for by increasing the C/N appropriately.

2.9.2 Required C/I for MSAT-2

The discussion in Section 2.9.1 has demonstrated that the C/I requirement can be lowered by increasing the transmitter power for the analog voice. Since the MSAT-2 baseline assumes all services will be digital, the question whether an overall C/I lower than 17 dB is acceptable remains to be answered. The effect of interference on a modem generally depends on the specific type of modulation and demodulation schemes, and accurate prediction is often difficult. In order to assess the interference effect on a digital modem using the baseline modulation scheme, i.e., GMSK, simulation has been performed using the channel simulator.

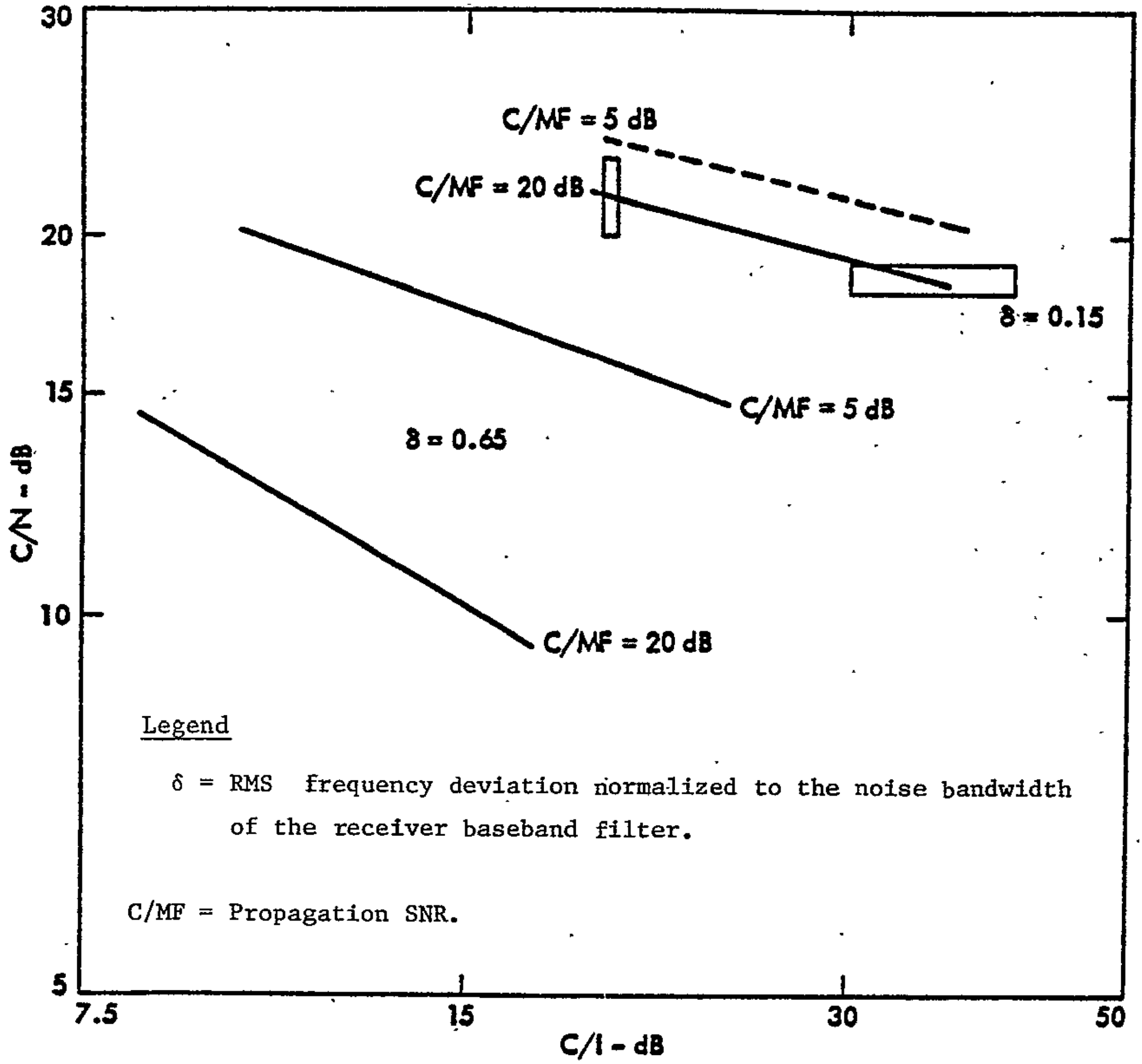
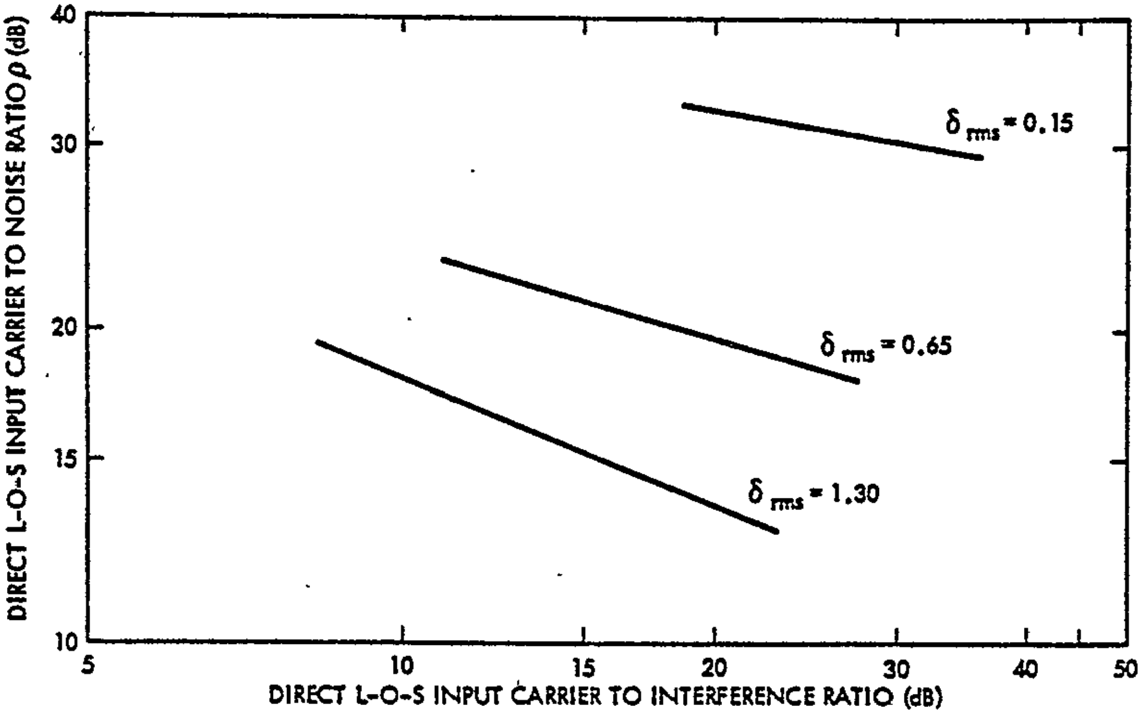


Figure 2-45. Acceptability Thresholds as a Function of C/N and C/I for Two Values of C/MF and Two Values of δ



Legend

δ_{rms} = RMS frequency deviation normalized to the noise bandwidth of the receiver baseband filter.

Figure 2-46. Acceptability Thresholds of Narrowband FM Voice in a Rayleigh Fading Environment

Some preliminary results have been obtained and are shown in Figure 2-47 for three operating points, at a bit error rate (BER) of 1.4×10^{-2}, 1.5×10^{-4}, and 3.0×10^{-5}. Based on the simulation results, it is clear that a digital system can also operate at a C/I below 17 dB, provided that it is within a reasonable range and the transmitter power can be appropriately increased. Consequently, there will be no preset hard limit on the minimum C/I value. Instead, a practical, achievable value will be established by considering a host of variables that affect the overall C/I value. Specifically the required C/I will be whatever is achievable for the 20-m, single-feed, 7-frequency reuse system.

2.9.3 The Achievable Overall C/I

The overall C/I is a function of the antenna sidelobe level, adjacent satellite isolation, intermod level, etc. In addition, it varies as a function of the communication modes and is most severe for the mobile-to-mobile communications. Appendix E presents a detailed analysis of the interference environment. Figures 2-48, 2-49, and 2-50 illustrate the overall C/I as a function of other variables for the mobile-to-mobile, mobile-to-fixed-station, and fixed-station-to-mobile communications, respectively. Referring to these figures, I_B denotes the interbeam isolation or antenna isolation, I_S is the intersatellite or adjacent satellite isolation, and I_M is the carrier to intermodulation product isolation. The overall C/I in Figures 2-48 and 2-50 is presented with I_{MS} as a function of the intersatellite isolation and the carrier-to-intermod isolation. The achievable intersatellite isolation for a two-satellite system is approximately 23 dB, based on the current estimate, and the intermod isolation is 24 dB (see subsections 2.8.4 and 2.8.5). Using these two values the I_{MS} is found, from Figure 2-48, to be about 20.5 dB. To achieve an overall

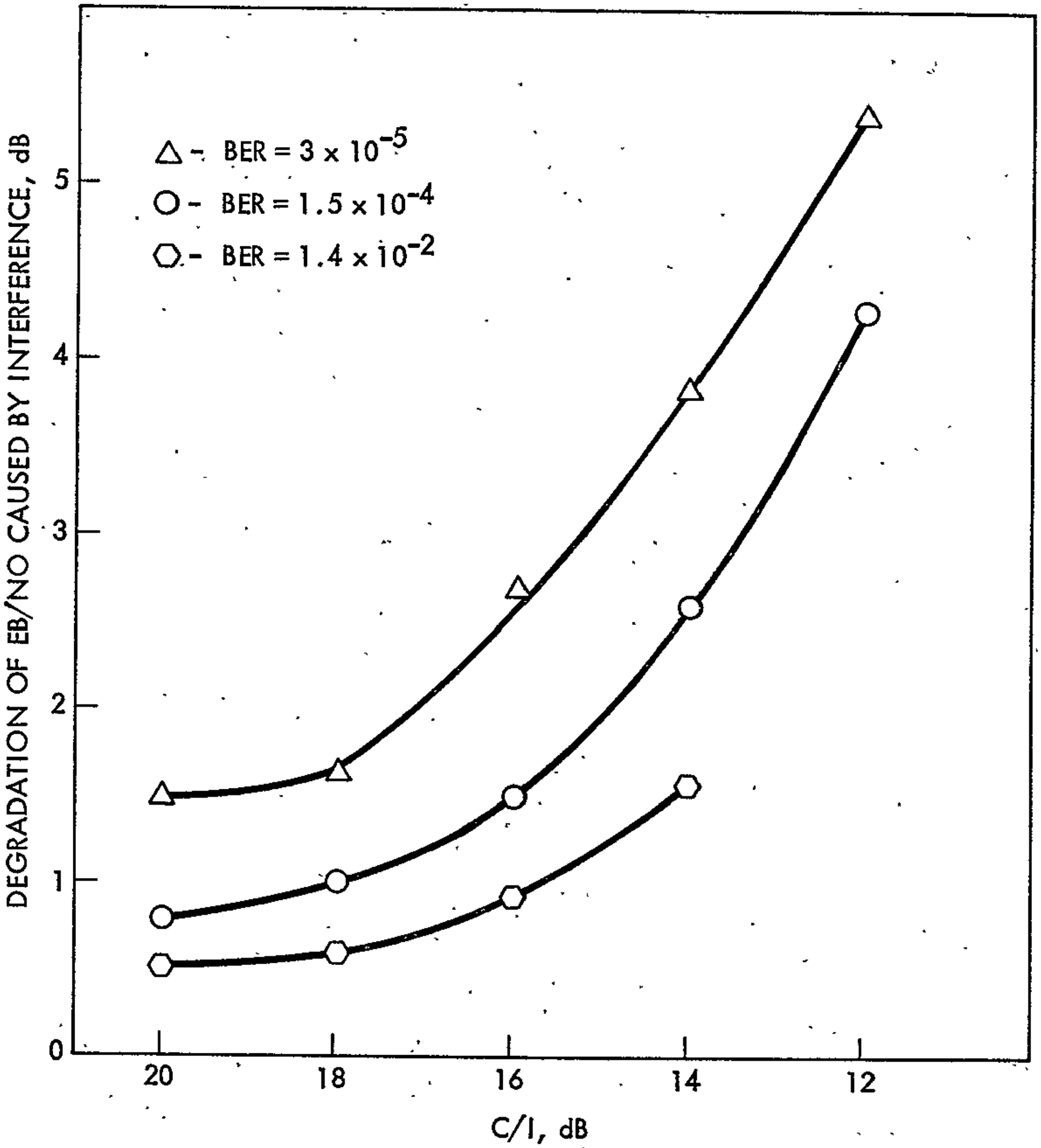


Figure 2-47. Effects of Cochannel Interference on a Digital System Using GMSK Modulation With Coherent Detection, Channel Simulator Results (Preliminary).

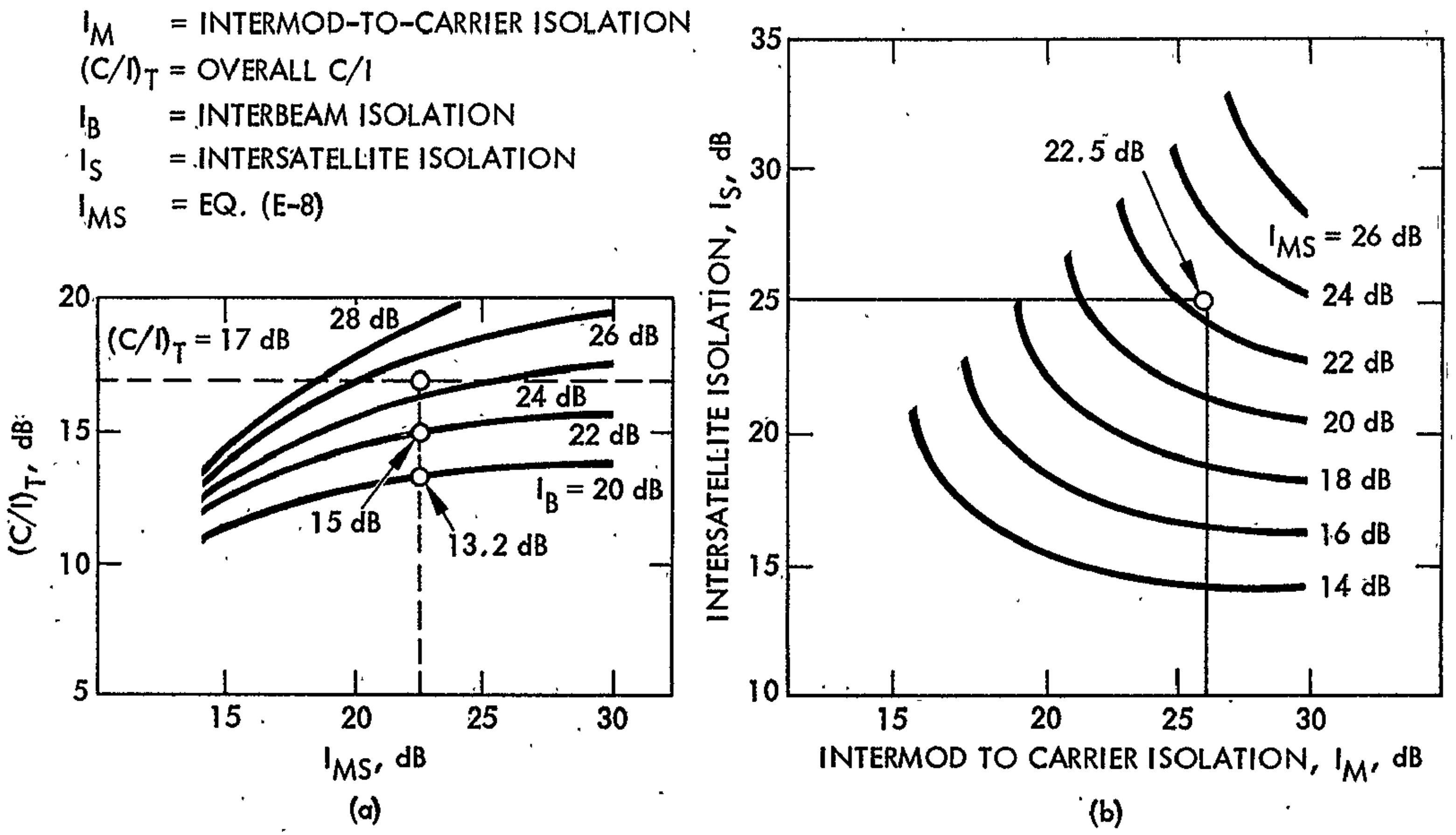


Figure 2-48. Overall C/I, Intersatellite Isolation, Interbeam Isolation, and Intermod-to-Carrier Isolation (Mobile-to-Mobile).

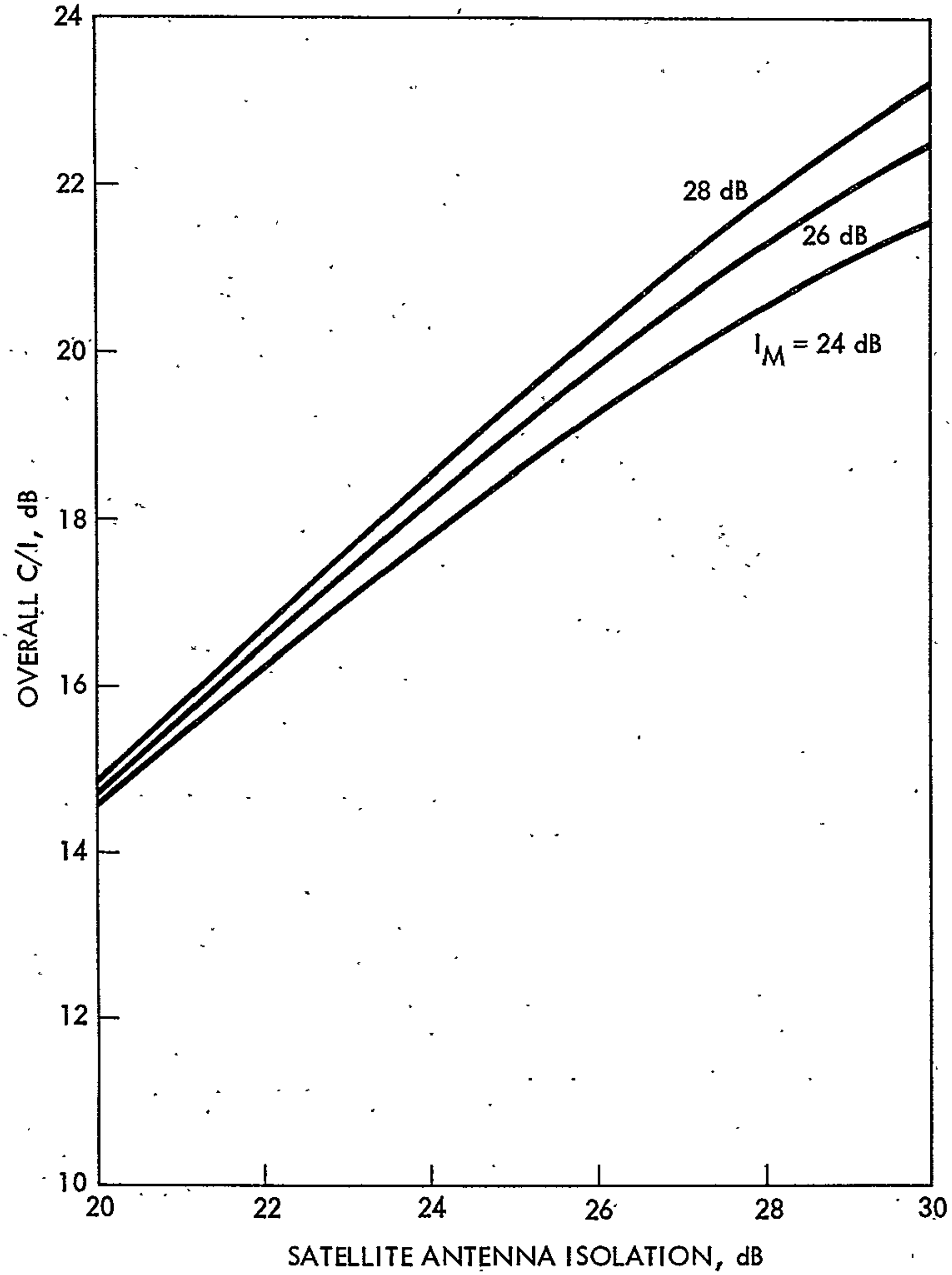


Figure 2-49. Overall C/I vs. Satellite Antenna Isolation With I_M as a Parameter.
Mobile-to-Fixed-Station.
I_M = Carrier-to-Intermod Ratio (Backhaul).

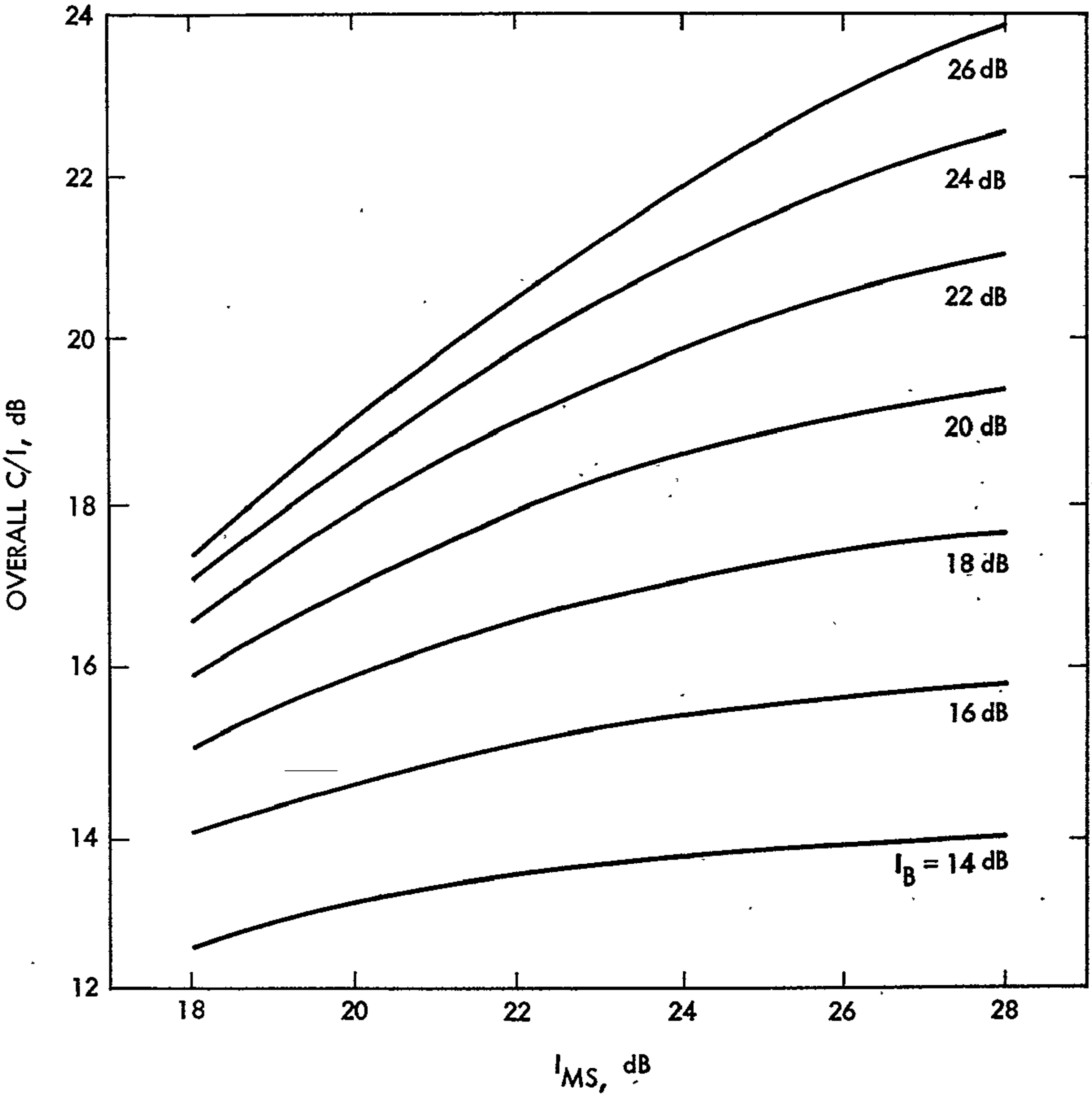


Figure 2-50. Overall C/I vs. I_{MS} for Selected Satellite Antenna Isolation. Fixed-Station-to-Mobile.
I_{MS} is Defined in Eq. (E-8).
I_B = Interbeam Isolation.

C/I of 17 dB, the interbeam isolation must be at least 25 dB for the mobile-to-mobile case, which would require an overlapping feed. In order to take advantage of the simplicity and light weight of the single feed design, the overall C/I will have to be relaxed. For the selected design, which has an interbeam isolation of 20 dB and a frequency reuse factor of 7, the achievable overall C/I is approximately 13 dB for mobile-to-mobile communications and 17 dB for fixed-station-to-mobile communications. Even though a 13-dB C/I will require more satelite power than a 17-dB C/I would, the analysis in Section 2.8 showed that the single feed design still offers more channels than the overlapping feed design when the entire system is considered. One of the reasons for this is that the low C/I value is associated with mobile-to-mobile communications which account for only 10% of the total traffic. Another reason is that the benefit of a higher C/I using an overlapping feed design is more than offset by the disadvantage of a heavier feed. The achievable C/I for the mobile-to-fixed-station case is about 14.5 dB assuming that the intermod isolation for the backhaul link is the same as the UHF link, i.e., 24 dB.

In establishing the achievable overall C/I, requirements have been imposed on the intersatellite isolation and intermod level, i.e., 23 dB and 24 dB, respectively. Are these requirements practical? Can a more stringent requirement be imposed on one or both of these two parameters in order to improve the overall C/I or to relax the requirement on the other? These questions will be examined in the following sections.

2.9.4 The Required Intersatellite Isolation

Similar to the requirement regarding overall C/I, the required intersatellite isolation is the achievable isolation. Based on work performed by MSAT-X,

the combined pattern and polarization isolation for a medium-gain mobile antenna operating in a two-satellite environment is about 15 to 20 dB in the absence of multipath fading. An additional isolation of about 5 dB can be realized by staggering the frequency channels of one satellite with respect to the other, giving a total isolation of 20 to 25 dB.

For MSAT-2, an isolation of 25 dB is assumed. (It is noted that the intersatellite isolation being addressed here is for the service link (UHF). The intersatellite interference for the backhaul link (Ku) is assumed to be negligible.)

The presence of multipath fading can lower the isolation. The extent to which it is lowered depends on whether the signals from the two satellites are independently faded or not. If they are truly independently faded, then the isolation can be reduced by 5 dB. On the other hand, if they undergo the same fading environment, then there will be no effect on the isolation. While the extent and the effects are currently being investigated, a moderate 2 dB will be budgeted to account for multipath fading. This brings the isolation to 23 dB.

While there is a degree of flexibility in establishing the required intersatellite isolation, its range is narrow. A much higher isolation, say 25 to 28 dB, is believed to be unrealistic and not necessary. Based on a 24-dB intermod isolation and a 20-dB interbeam isolation, it can be seen from Figure 2-49 that the overall C/I for the mobile-to-mobile case where the interference is most severe is relatively insensitive to the intersatellite isolation. For example, raising its value from 23 dB to 25 dB can only increase the I_{MS} from 20.5 to 21.5 dB, which in turn improves the overall C/I from 13 to about 13.1 dB, a negligible amount of improvement.

Similarly, a higher intersatellite isolation is not expected to produce appreciable effects for the other two modes of communications. The C/I for the mobile-to-fixed-station case is determined by the interbeam isolation and intermod isolation as indicated in Figure 2-49. Hence, it is not affected by the intersatellite isolation. Although the C/I for the fixed-station-to-mobile communications can benefit from a higher intersatellite isolation, it is not significant enough to result in an appreciable power savings, which ultimately determines the capacity and cost of the system. An increase of 2 dB in the intersatellite isolation from the present 23 dB would bring the C/I from 17.2 dB to about 17.7 dB, or a moderate gain of 0.5 dB. The 0.5 dB increase, however, would result in less than 0.1 dB power savings for each channel operating in the fixed-station-to-mobile mode.

While an intersatellite isolation much higher than 23 dB is not necessary for MSAT-2 and is probably not realistic, a much lower isolation may be unacceptable. The overall C/I is a function of both the intersatellite isolation and the intermod isolation. It appears one may relax the intersatellite requirement without degrading the C/I performance by increasing the intermod isolation. Lowering the intersatellite isolation, say by 1 or 2 dB, would require an intermod isolation that is 2 to 6 dB higher than the assumed isolation of 24 dB (see section 2.8.5). To achieve an intermod isolation of 28 to 30 dB is not practical.

2.9.5 The Required Intermod Isolation

The required intermod level, or the intermod isolation, is 24 dB. This value is based on information obtained from the satellite manufacturers and is sufficient for MSAT-2 for several reasons.

First, the intermod isolation similar to the intersatellite isolation does not have a significant impact on the overall C/I for the mobile-to-mobile and fixed-station-to-mobile communications as shown in Figures 2-48 and 2-50. Secondly, although it is possible to improve the overall C/I for the mobile-to-fixed-station communications by raising the intermod isolation, the price would outweigh the benefit. For example, in order to raise the overall C/I by 0.5 dB, the intermod would have to be raised from 24 to 28 dB. Increasing the intermod isolation to 28 dB would reduce the efficiency and the loss would be greater than the gain. The 24-dB isolation is thus considered a practical value for MSAT-2.

2.10 STATION-KEEPING REQUIREMENT

A satellite launched in a geostationary orbit is perturbed by external forces such as the gravitational pull of the sun and the moon, and the anomalies in the gravitational field of the earth. These forces cause the satellite to drift in both the east-west and north-south directions, resulting in a change in satellite longitude and inclination. The change of location causes the satellite footprint to move on the ground. Depending on the ground antenna beamwidth, satellite tracking may be necessary or a loss of antenna gain may occur. The change in satellite inclination has a further implication for the second-generation mobile satellite system, which is designed to provide reliable service to CONUS, Alaska, and Canada. The locations of the satellites have been chosen to

maintain a minimum elevation angle of 10 degrees for most of the covered area. The 10-degree elevation angle was selected by considering the propagation effects, mobile antenna complexity and cost, and link performance. With the north-south movement, loss of coverage may result in the northern part of Canada and Alaska. The satellite can be kept in the desired orbit and, hence, the loss of coverage can be avoided if the satellite is designed with full station-keeping capability. This capability however must be paid for in terms of increased satellite weight or reduced spacecraft power, both of which are precious. The advantages and disadvantages for having full station-keeping capability will be examined and a requirement will be established.

2.10.1 Weight Savings

The amount of east-west drift of a geostationary satellite due to anomalies in the gravitational field of the Earth varies as a function of the satellite longitude. Figure 2-51 [16] shows the amount of station-keeping velocity required to compensate for the east-west movement. The MSAT-2 baseline design has selected a location at 90-degrees and 130-degrees west longitude. At these locations, the amount of station-keeping is less than 1 m/sec per year. With a spacecraft design life of 10 years, the total amount of east-west station-keeping velocity is less than 10 m/sec. The amount of propellant required can be estimated as a percentage of the end-of-life (EOL) spacecraft mass, W_{SC}.

$$\begin{bmatrix} \text{Amount of east-west} \\ \text{station-keeping fuel} \\ \text{normalized to } W_{SC} \end{bmatrix} = \exp\left(10 \text{ m/s } /((\text{ISP})(9.8 \text{ m/S}^2))\right) - 1 = 0.003$$

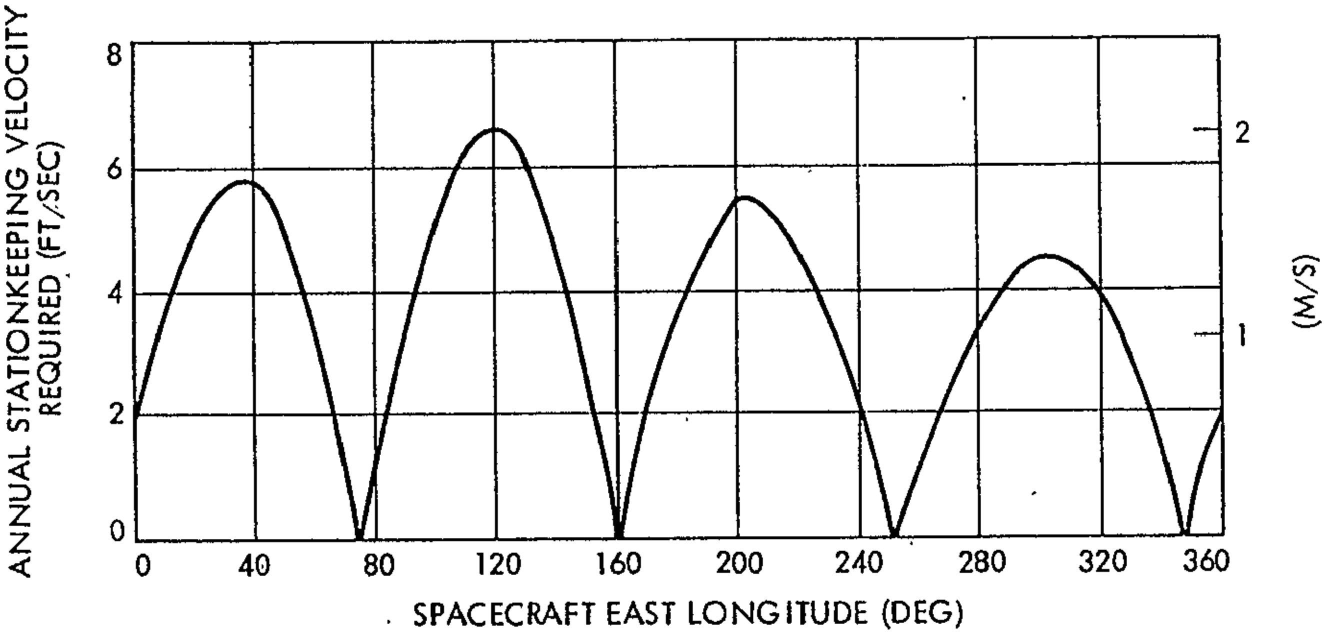


Figure 2-51. Required East-West Station-Keeping Velocity as a Function of Spacecraft Longitude

where ISP is the specific impulse of the propellant which is expected to range from 250 to 300 seconds. For the purpose of this tradeoff, the ISP has been assumed to be 300 seconds. The propellant mass is less than one-half of one percent of the EOL spacecraft mass. This is insignificant relative to the north-south station-keeping fuel which will be addressed later. Eliminating the east-west station-keeping would not reduce the spacecraft's weight significantly. In addition, the amount of east-west drift would probably be too large to be acceptable. Current international radio regulations require a communications (fixed) satellite to be station kept in the east-west direction to $\pm$ 0.1 degrees. East-West station-keeping will therefore be required for MSAT-2.

In contrast to the east-west station-keeping, the north-south station-keeping fuel contributes a significant amount to the total spacecraft mass. The north-south movement is approximatley 0.9 degrees per year. For a 10-year spacecraft, the total amount of drift is about 9 degrees. The amount of velocity change is about 46 m/sec per year [16]. During the 10-year life of the spacecraft, a total velocity change of (46 m/s) x (10) = 460 m/s is required. The amount of fuel required can be estimated as follows:

$$\begin{bmatrix} \text{Amount of north-south} \\ \text{station-keeping fuel} \\ \text{normalized to } W_{SC} \end{bmatrix} = \exp(460\text{ m/s}/((300\text{s})\cdot(9.8\text{ m/s}^2)))-1 = 0.17$$

About 17% of the EOL spacecraft is for north-south station-keeping compared to a negligible 0.3% required for east-west station-keeping. Eliminating north-south station-keeping would therefore result in a significant reduction in spacecraft weight.

The weight capability of the satellite bus/launch vehicle considered for MSAT-2 is about 2500 kg at the geostationary transfer orbit or about 1300 kg at the beginning of life (BOL). Assuming 10% of the BOL mass is allocated for east-west station-keeping and the initial orbit correction, the EOL spacecraft mass would be about 1170 kg. The weight reduction due to the elimination of north-south station-keeping is therefore approximately 198 kg (1170 Kg x 0.17 = 198 kg). This is a significant reduction!

2.10.2 Increase In Spacecraft Power

The weight savings for not having north-south station-keeping can be translated directly into an increase in the spacecraft power and, consequently, the number of satellite channels. Figure 2-7 shows the baseline payload power vs. payload weight curve. It has a slope of 9.2 W/kg. The 198 kg weight reduction can thus be utilized by the power subsystem and generate approximately 1800 watts (9.2 W/kg x 198 kg = 1821 watts) of spacecraft power. Assuming a DC-RF conversion efficiency of 26%, an additional 473 watts of RF would be available, which could power up thousands of channels. The increase in satellite channels is indeed significant.

2.10.3 Adverse Effects

While the gain in satellite channels and power is impressive, the price for not having north-south station-keeping is also very high. Without north-south station-keeping, the satellite can drift approximately a total of 9 degrees in 10 years, as mentioned before. If the satellite orbit is intentionally biased at launch by half of that amount, 4.5 degrees, then the satellite will move in the course of its lifetime from 4.5 degrees on one side of the geostationary orbit through 0 degrees to 4.5 degrees on the other

side of the orbit. The inclination causes the satellite to produce a figure-8 footprint on Earth. The figure-8 movement in turn causes the Earth-to-satellite elevation and azimuth angles to vary. The worst case variation in azimuth angle caused by orbit inclination is approximately given by:

$$\sin^{-1}[1.18 \tan^2 (i/2)]$$

where i denotes the orbit inclination. At the maximum inclination of 4.5 degrees, the change in azimuth angle is about 0.1 degrees, which is negligible compared to the azimuth beamwidth of the mobile antenna.

While the change in azimuth angle is negligible, the change in elevation angle is not. At an inclination of 4.5 degrees, the elevation angle at the subsatellite point varies in a 24-hour period by approximately $\pm$ 5.3 degrees about the nominal value when the satellite inclination is zero. The amount of variation decreases to about 4.6 degrees as the latitude of the mobile terminal increases to about 70 degrees. Table 2-16 tabulates the mobile-terminal-to-satellite elevation angle for selected mobile locations for two geostationary satellite locations: one at 90 degrees west longitude with a 0 degree inclination and the other at the same longitude, but 4.5 degrees south of the equator. This table assumes a normal road condition for the mobile vehicle, i.e., a flat surface.

The variation in elevation angle creates two problems. The first problem is a possible loss of mobile antenna gain. Current mobile antenna development work is focused on medium-gain antennas. The beam pattern of this type of antenna is narrow in the azimuth direction but relatively broad in the elevation direction. Because of the narrow azimuthal beam, some kind of tracking mechanism is required in this direction. However, the mobile terminal may not have a tracking capability in the elevation direction. The mechanical MGA currently conceived is capable of providing a minimum gain of 10 to 12 dBi for elevation angles ranging from 20 to 60 degrees. Operating outside these

Table 2-16.

Elevation Angle For Selected Mobile Locations

Under Normal Road Conditions

Mobile Terminal Location (degrees) West Longitude	Latitude	Elevation Angle to a Geostationary Satellite at 90° W with Zero Degrees Inclination (degrees)	Elevation Angle to a Geostationary Satellite at 90°W and 4.5 Degrees South of the Equator (degrees)	Difference In Elevation Angles (degrees)
90	0	90.0	84.7	5.3
90	30	55.0	49.9	5.1
90	40	43.7	38.7	5.0
90	60	21.9	17.2	4.7
90	70	11.5	6.9	4.6
100	70	11.2	6.6	4.6
110	70	10.2	5.6	4.6
120	70	8.6	4.1	4.5

limits will result in a loss of gain. The amount of loss depends on the particular antenna pattern and how far it is from the limits. The elevation angle of a geostationary satellite with no inclination ranges from approximately 25 to 60 degrees for CONUS. Under normal operating conditions, the drift of the satellite should have little impact. However, due to adverse road conditions such as a steep grade, the elevation angle may exceed 60 degrees in some locations. The drift of the satellite, therefore, may cause the mobile-to-satellite line-of-sight to move further away from the 60-degree limit, resulting in a loss of antenna gain. This is likely to happen in the extreme southern parts of CONUS, such as the South of Florida and Brownsville, Texas. Table 2-17 shows the variation in elevation angles for two southern locations under normal road conditions with the satellite at 4.5 degrees north of the equator.

The second problem, due to the variation in elevation angle, is a possible loss of coverage. For mobile terminals operating in the northern part of the covered area where the nominal mobile-to-satellite elevation angle is low to start with, the variation makes it even lower during part of the day and a minimum 10-degree elevation may not be possible to maintain. An adequate link margin is very difficult to achieve at an elevation angle below 10 degrees where multipath fading is expected to be very severe and where LOS may not even exist. A plot of the constant 10-degree elevation contours is shown in Figures 2-52 and 2-53 for the east and west satellites. In each of these plots, the 10-degree contour is shown for the case in which the satellite inclination is zero (top curve) and the case in which the satellite is 4.5 degrees south of the equatorial plane (bottom curve).

2.10.4 Possible Approaches to Minimize the Adverse Effects

The loss of mobile antenna gain due to operations at an elevation angle above 60 degrees can be avoided through operational constraints. By adjusting the

Table 2-17.

Elevation Angle For Selected Mobile Locations

Under Normal Road Conditions

Mobile Terminal Location (degrees) West Longitude	Mobile Terminal Location (degrees) Latitude	Elevation Angle to a Geostationary Satellite at 90° W with Zero Degrees Inclination (degrees)	Elevation Angle to a Geostationary Satellite at 90°W and 4.5 Degrees North of the Equator (degrees)	Difference In Elevation Angles (degrees)
81	25	59.1	63.5	5.0
97.5	26	58.5	63.9	4.9

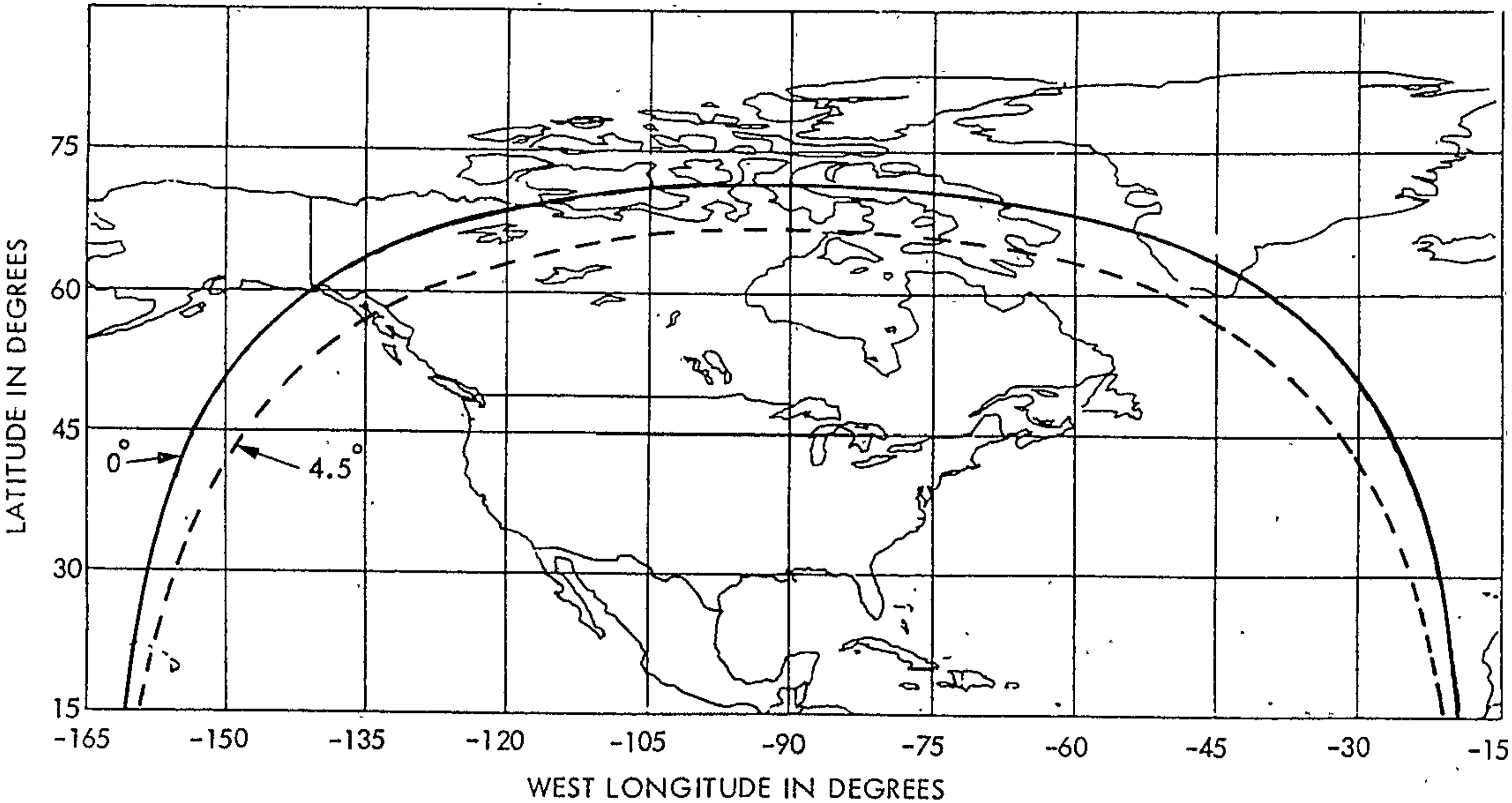


Figure 2-52. Contours of Constant Elevation Angle (10 Degrees) for the East Satellite with 0 and 4.5 Degrees Inclination

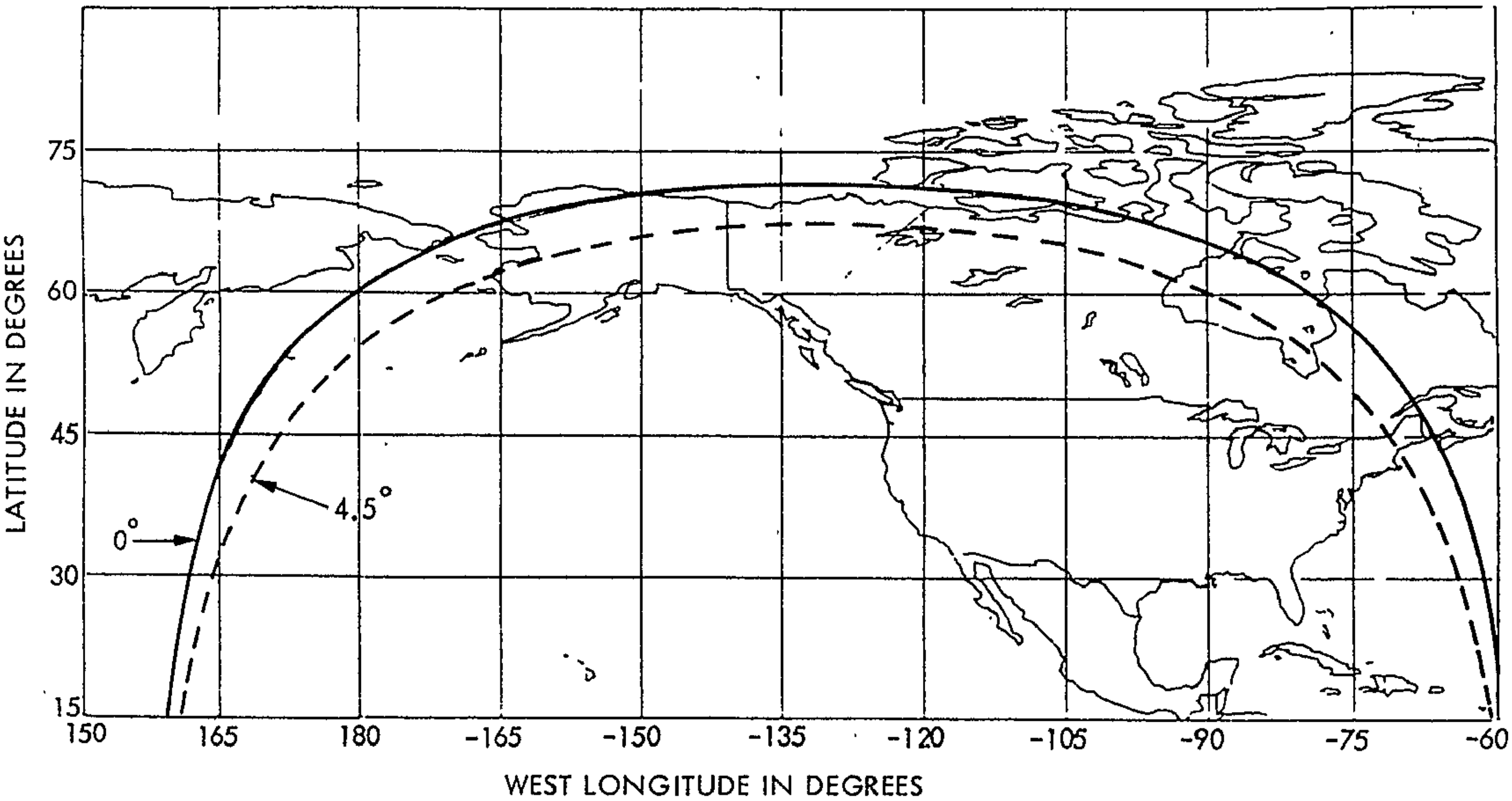


Figure 2-53. Contours of Constant Elevation Angle (10 Degrees) for the West Satellite with 0 and 4.5 Degrees Inclination

antenna pointing (in the elevation direction), it is possible to restrict the line-of-sight signal to stay within a prescribed limit under normal operating conditions. No loss of gain would therefore occur even if the satellite drifts. The adjustment of antenna pointing may be a required procedure for a mechanical MGA even in the absence of satellite drift. This is because of the wide range of elevation angles contained in the service area. While the antenna gain loss due to large elevation angles can be avoided through operational constraints, the loss of coverage area cannot be readily remedied. Although it is possible to point the antenna at a lower elevation angle in order to increase the gain on the LOS signal, the increase in multipath will probably more than offset the gain. Even with a specially designed antenna, reliable service cannot be guaranteed because LOS may not exist. In addition, such an antenna will probably be too costly and complex to be practical.

2.10.5 Requirements

There is no doubt that east-west station-keeping will be needed in order to comply with existing international radio regulations and to maintain a proper coverage. The decision on the north-south station-keeping, however, is not that obvious. There are significant advantages and disadvantages for having or not having full north-south station-keeping. The tradeoff is not purely a technical one and it may be subjective. Considering the coverage requirement and the potential gain in system capacity, a partial north-south station-keeping will be required as a compromise to maximize the capacity and to reduce the loss of coverage area. Table 2-18 tabulates the savings of station-keeping fuel and the amount of additional RF power for selected station-keeping requirements, assuming that all the weight savings can be applied to increase the payload power. Based on this table and the coverage requirement, it was decided to station keep the satellite within 2 degrees of the orbit.

Table 2-18.

The Impact of North-South Station-Keeping on the Available Power

North-South Station-Keeping Requirements (degrees)	Savings on Station-Keeping Fuel (kg)	Additional Available RF Power (watts)	Comments
0.0	0	0	Full station-keeping
±1.0	47	112	
±2.0	92	220	
±3.0	135	322	
±4.0	177	423	
±4.5	198	473	No north-south station-keeping

The resulting coverage area is shown in Figures 2-54 and 2-55 for the 90-degree and 130-degree satellites, respectively. The loss of coverage has been reduced substantially as evidenced in the figures. The amount of additional RF power is estimated to be 220 watts. The estimated RF power level for the baseline design is thus about 500 watts for a 2-degree north-south station-keeping. The variation of the mobile-to-satellite elevation angle in the southern-most area is shown in Table 2-19 for the east satellite with an inclination of 2 degrees. As indicated in the table, the variation is only about 2.2 degrees, which is expected to have minimal effects on the mobile antenna gain. The 2-degree requirement is thus judged to be acceptable.

2.11 ECLIPSE CAPABILITY

During eclipse, the required satellite power must be provided by the batteries on board the spacecraft. Batteries are heavy. For a power-limited or weight-limited system, it is essential to properly determine the required number of batteries. The eclipse capability for MSAT-2 is determined by considering the traffic demands during eclipse and the potential weight savings.

2.11.1 Traffic Demands

The traffic loading of a terrestrial telephone or mobile phone system exhibits both long-term and short-term variations. The long-term changes include seasonal and month-to-month variations. The short-term changes are the day-to-day and hour-to-hour variations. Similar variations are expected for the mobile satellite system although the actual traffic pattern is not known.

Figure 2-56, obtained from [17], shows the actual hourly traffic loading of a cellular system for one cell site on a Friday, and Figure 2-57, also from [17], is for the same cell site but on a Thursday. Both figures show the traffic

Table 2-19.

Elevation Angle for More Selected Mobile Locations

Under Normal Road Conditions

Mobile Terminal Location (degrees) West Longitude	Latitude	Elevation Angle to a Geostationary Satellite at 90° W With No Inclination (degrees)	Elevation Angle to a Geostationary Satellite at 90°W and 2 Degrees North of the Equator (degrees)	Difference in Elevation Angle (degrees)
81	25	59.1	56.9	2.2
97.5	26	58.5	56.3	2.2

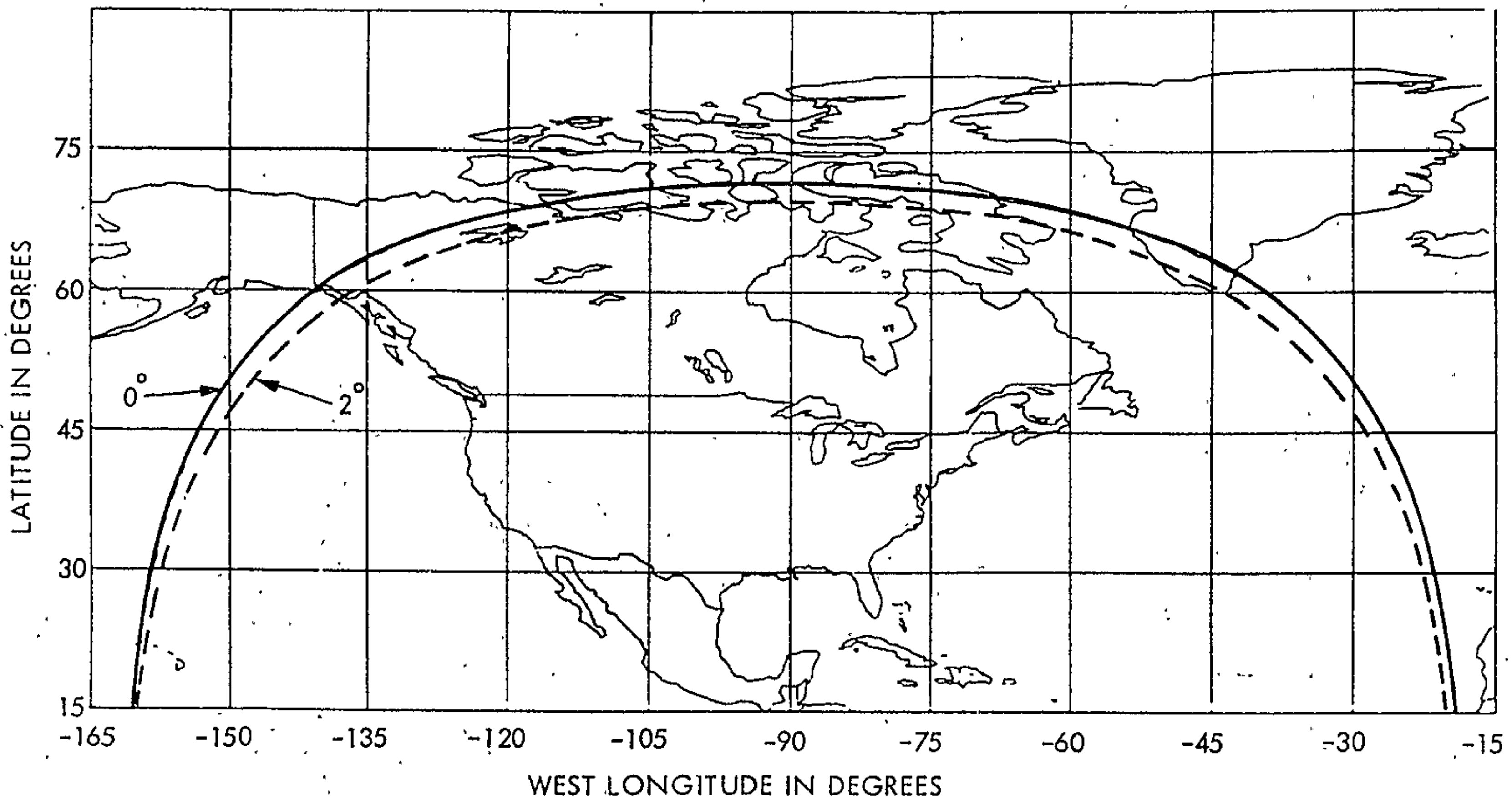


Figure 2-54. Contours of Constant Elevation Angle (10 Degrees) for the East Satellite with 0 and 2.0 Degrees Inclination

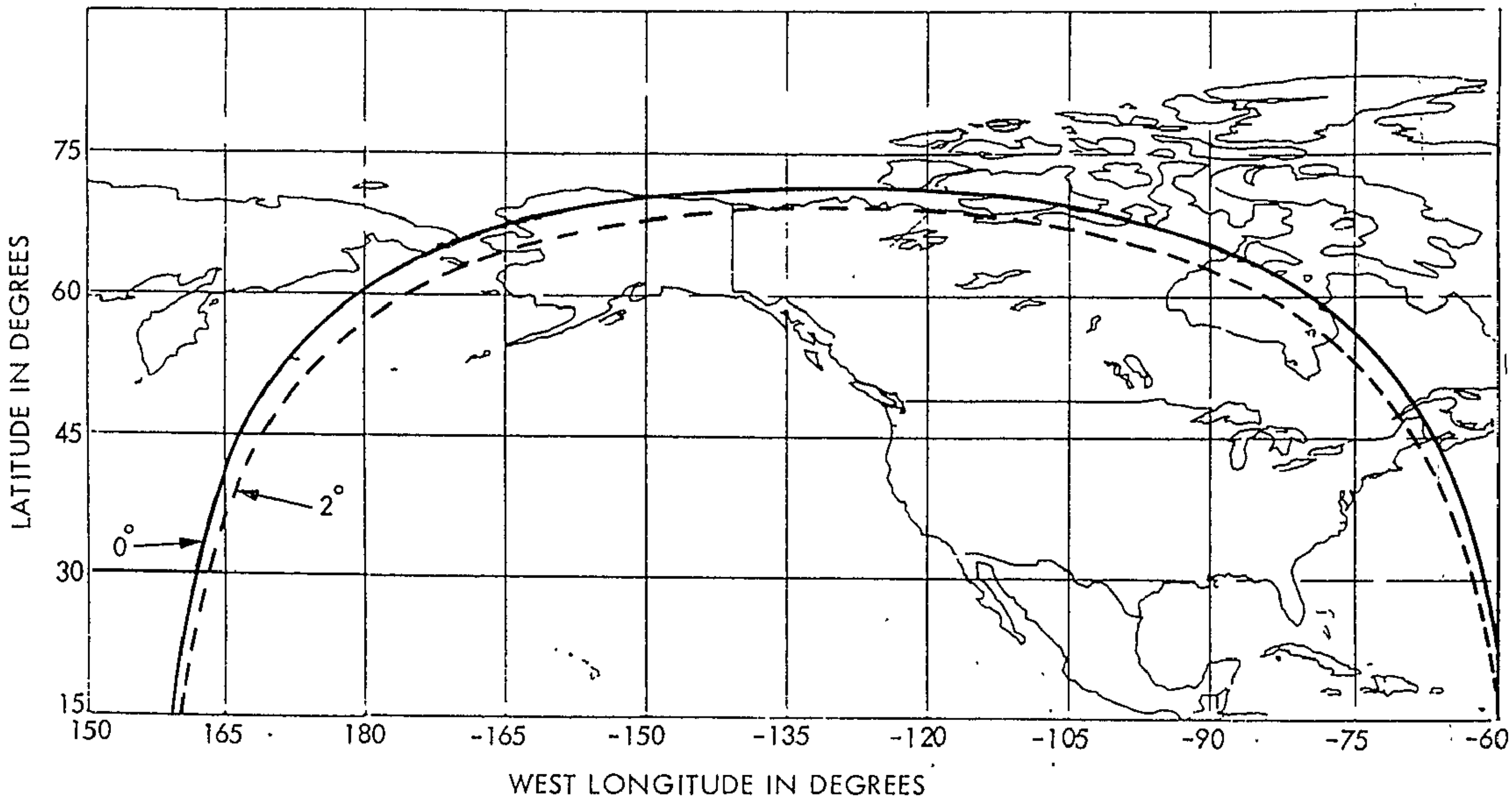


Figure 2-55. Contours of Constant Elevation Angle (10 Degrees) for the West Satellite with 0 and 2.0 Degrees Inclination

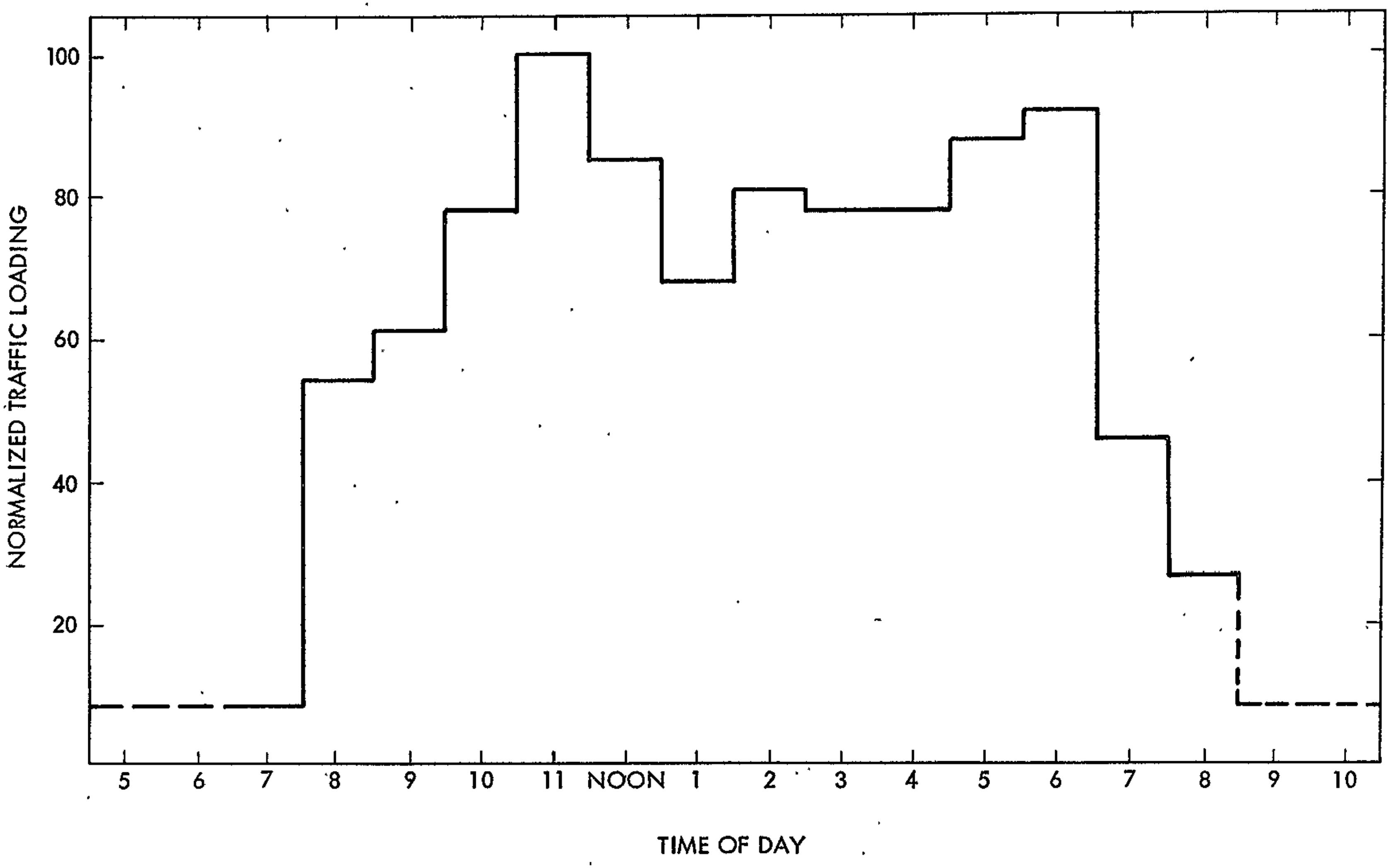


Figure 2-56. Friday Hourly Traffic Loading for a Cell Site of a Cellular System [17]

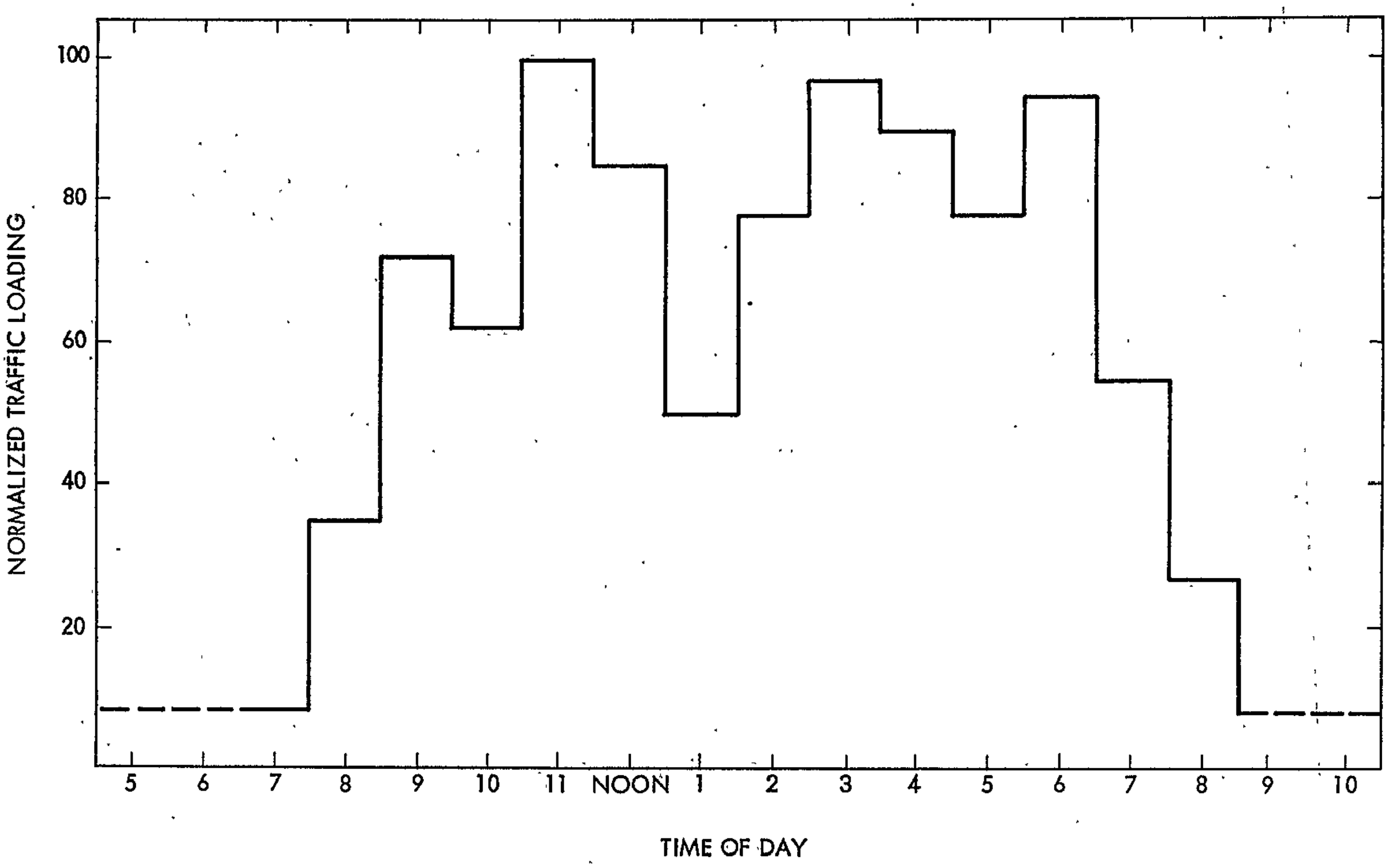


Figure 2-57. Thursday Hourly Traffic Loading for a Cell Site of a Cellular System [17]

first peaks at about 11:00 a.m., falls off during noon, and starts to pickup and reaches a second peak in the afternoon, about 3 to 6 hours after the first peak. Roughly, these patterns exhibit the same general characteristics as observed on the telephone system. Although the hourly traffic loading of a cellular system varies from site to site in addition to the above day-of-the-week variation, it is assumed, in the lack of actual data and for the purpose of simplification, that the traffic loading of a mobile satellite system can be modeled by Figure 2-57. The area served by MSAT-2 encompasses four time zones, excluding Alaska. Assuming the traffic pattern in each time zone behaves the same as Figure 2-57, the total traffic pattern of the system is the weighted sum of four identical but time-shifted patterns obtained by shifting the pattern in Figure 2-57 by 0, 1, 2, and 3 hours. Different weights are necessary because the number of projected users in each time zone is different. Based on Figure 2-1, which shows the user density, the ratio of the users in the four time zones is approximately 4 : 4 : 1 : 1 with the eastern and central time zones having the most users. The total traffic pattern is shown in Figure 2-58 for two users ratios: 1 : 1 : 1 : 1 and 4 : 4 : 1 : 1. The latter will be used as the baseline traffic model for MSAT-2. In deriving the pattern, the traffic loading of a given time zone after 8:00 p.m. has been assumed to stay at a constant level, equal to 10% of its peak, until 7:00 a.m. next morning. The time shown in the figure is the eastern time.

Eclipse occurs near the local midnight, at the subsatellite point. The locations of the MSAT-2 satellites are 90 degrees and 130 degrees west longitude. The traffic loading during eclipse is estimated to be about 10%. The RF power output during eclipse is therefore about 10% of the peak RF power output.

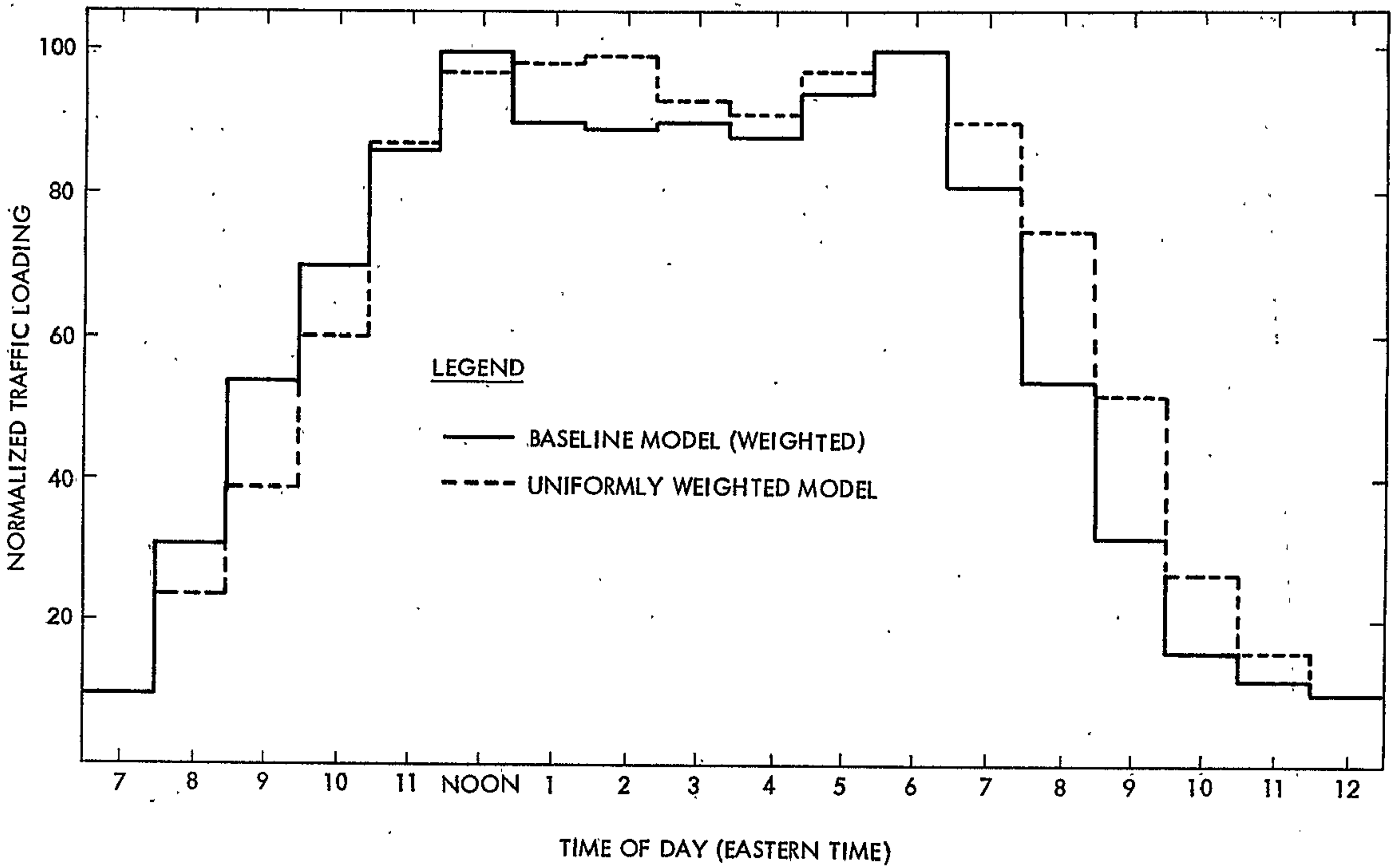


Figure 2-58. Assumed Traffic Loading Model for MSAT-2.

2.11.2 Requirements

The required satellite power during eclipse, however, will be higher than 10% of the peak because the efficiency of the power amplifiers on board the satellite becomes poorer at a lower output power level. When operating at the designed power output, which corresponds to an OBO of about 4 dB for a linearized HPA, the DC-to-RF efficiency is about 26% including the efficiency of the power conditioners. To reduce the output power to about 10% of the design output power means an additional output back off of 10 dB from the normal operating point, and the efficiency is expected to be lower. As a conservative approach, the power requirement during eclipse is 50%.

The reduced eclipse capability results in a fewer number of batteries on board the spacecraft, which in turn reduces the weight of the spacecraft. For a typical second-generation satellite operating at 2 to 4 kW of power, the estimated weight savings is in the range of 50 to 100 kg. This weight reduction in turn can be used to increase the payload power. The amount of additional power is estimated to be in the range of 0.4 to 1.5 kW, which is about 20 to 40% of the total payload power.

The traffic loading is basically a random variable. Although the traffic demand during eclipse is expected to be lower, by reducing the eclipse capability to 50% there is a small but finite probability that the actual demand may exceed the designed capacity. This is the price for the reduced eclipse capability. Because the designed capability is five times the projected traffic demand, the probability is expected to be very small. Considering the amount of weight savings, the price is judged to be acceptable.

REFERENCES

[1] Requirement for a Mobile Communications Satellite System, Volumes 1 and 2, TRW Report, April 11, 1983.

[2] Mobile Radio Alternative Systems Study, Volume III, Satellite/Terrestrial (Hybrid) Systems Concepts, John D. Kiesling and Roy E. Anderson, General Electric Company report, prepared for NASAS/Lewis Research Center under contract NAS 3-23244, June 1983.

[3] Mobile Communications Satellite (MSAT) Communications System Concept Document, Communications Research Center Department of Communications, Shirby Bay, Ontario, Canada, March 2, 1983.

[4] Requirements for a Mobile Communications Satellite System, Volume 2,d Technical Report, TRW Space and Technology Group, prepared for NASA/ Lewis Research Center under Contract NAS3-23257, April 1, 1983.

[5] Aviation Week and Space Technology, May 21, 1984.

[6] Land Mobile Satellite Service, Volume II, Technical Report, JPL Publication 82-19, Naderi, F., Editor, February 1982.

[7] Phased Arrays for Multibeam Communications Satellites, Technical Report, Grumman Aerospace Corporation, Contract NAS 8-35131, February 1983.

[8] Some Important Geometrical Features of Conic-Section Generated Offset Reflector Antennas, Jamnejad, V., Rahmat-Samii, Y., IEEE Trans. Antennas and Propagation, Vol. AP-28, P. 957, November 1980.

[9] Design, Fabrication and Testing of a Multibeam-Forming Network, Final Report, prepared by Western Development Laboratories, Ford Aerospace and Communications Corporation, JPL Contract 956722, September 1984.

[10] Multibeam Feed System Design Considerations for Single Aperture Large Space Antennas, Jamnejad, V., NASA Conference Publication: Large Space Antenna Systems Technology-1984.

[11] Feed System Design Considerations for Multiple Aperture Large Space Antenna Systems, Bailey, M. C., NASA Conference Publication: Large Space Antenna Systems Technology-1984.

[12] Circularly-Polarized Microstrip Array with Wide Axial Ratio Bandwidth and Single Feed Linearly-polarized Elements, Huang, J., to be presented at IEEE/AP-S Symposium, Vancouver, Canada, June 1985.

[13] Development of a New Highly Efficient and Accurate Computer Code for Reflector Antennas, Jamnejad, V., JPL Internal Memo, 3365-84-001, January 1984.

[14] Mobile Satellite Configuration Study, Final Oral Report, RCA Astro-Electronics, January 23, 1985.

[15] Land Mobile Satellite Service (LMSS) Channel Simulator: An End-to-End Hardware Simulation and Study of the LMSS Communications Links, JPL Publication 84-12, Ali B. Salmasi, Editor, May 1, 1984.

[16] Land Mobile Satellite Service (LMSS): A Conceptual System Design and Identification of the Critical Technologies, Part II: Technical Report, JPL Publication 82-19, Firouz Naderi, Editor, February 15, 1982.

[17] Dynamic Channel Assignment, Cellular Resources, September-October, 1984.

CHAPTER 3

DESIGN OF THE BASELINE (UHF) SYSTEM

3.0 INTRODUCTION

This chapter presents a detailed design of the baseline second-generation mobile satellite system operating at UHF frequencies, i.e., the UHF system. The design in part is a direct result of the various trade-offs presented in Chapter 2. Chapter 2, however, is intended for second-generation mobile satellite systems in general. Some of its results are applicable to both the baseline system and the alternative system, i.e., the L-band system. The discussions in this chapter are specifically for the baseline design. The salient features of the baseline system will first be summarized, followed by a more detailed discussion on the spacecraft configuration, link budgets, transponder design, antenna/feed design; and finally the frequency plan, channelization, system capacity, and user cost will be addressed.

3.1 SALIENT FEATURES OF THE BASELINE SATELLITE SYSTEM

The basline system employs two satellites at 90 degrees and 130 degrees west longitude, providing services to CONUS, Canada, and Alaska. Multiple spot beams and frequency reuse schemes are employed in order to efficiently use the available bandwidth, which is assumed to be a pair of 10-MHz bands in the high UHF. To alleviate the burden on the mobile terminals and the spacecraft power subsystem, to reuse the limited RF spectrum, and to obtain the capacity needed to meet the projected demands, a moderately large, deployable antenna of 20 m is used. The packaging and control of such a large antenna poses a challenge to the satellite designers.

The number of beams required to adequately cover the service area is 24 and 21 for the east and west satellites, respectively. The satellites are built on a high-power communications satellite bus, and will have enough power for a total of 8688 channels, accommodating almost one million users based on a certain mixture of voice and data users (Section 3.12).

The major characteristics are given in Table 3-1.

3.2 SPACECRAFT CONFIGURATIONS

The most striking feature of the satellite is the 20-m reflector. The configuration of the spacecraft is primarily influenced by the configuration of the antenna and the Attitude Control Subsystem. Several configurations have been considered including center-fed, center-fed cassegrain, and offset-fed antenna geometries. Generally, center-fed configurations have an advantage over the offset configurations from a control point of view. The disadvantage, however, is the blockage of the field of view (FOV). Because of this blockage, center-fed configurations are not suitable for MSAT-2 (see Chapter 2). Six offset configurations have been examined and they are shown in Figures 3-1, 3-2, and 3-3.

Of the six offset-fed configurations, two have been selected for MSAT-2. These two configurations are identified in the figures as Configurations B-1 [1] and C-2.

From the control subsystem point of view, Configuration C-2 is preferable. In terms of stowage, B-1 is more compact (see Section 3.3). Further study is necessary in order to make a final selection. For the purpose of this study, both configurations appear feasible and, hence, both are considered as a possible candidate for MSAT-2. For convenience, these two configurations will be referred to as baseline configuration 1 and configuration 2.

Table 3-1.

Salient Features of the Baseline Design

Number of Satellites	2
Service Link Frequency	UHF
Backhaul Frequency	Ku
Number of Multiple Beams (UHF)	24 (East Sat.) 21 (West Sat.)
Number of Beams (Ku)	1
Antenna Size (Service Links)	20 m
Spacecraft Weight at GTO	2800 kg (6200 lbs)
Total Number of Satellite Channels	8688
Number of Users	900,000
Eclipse Capability	50%
North-South Station-Keeping Capability	$\pm$ 2 degrees

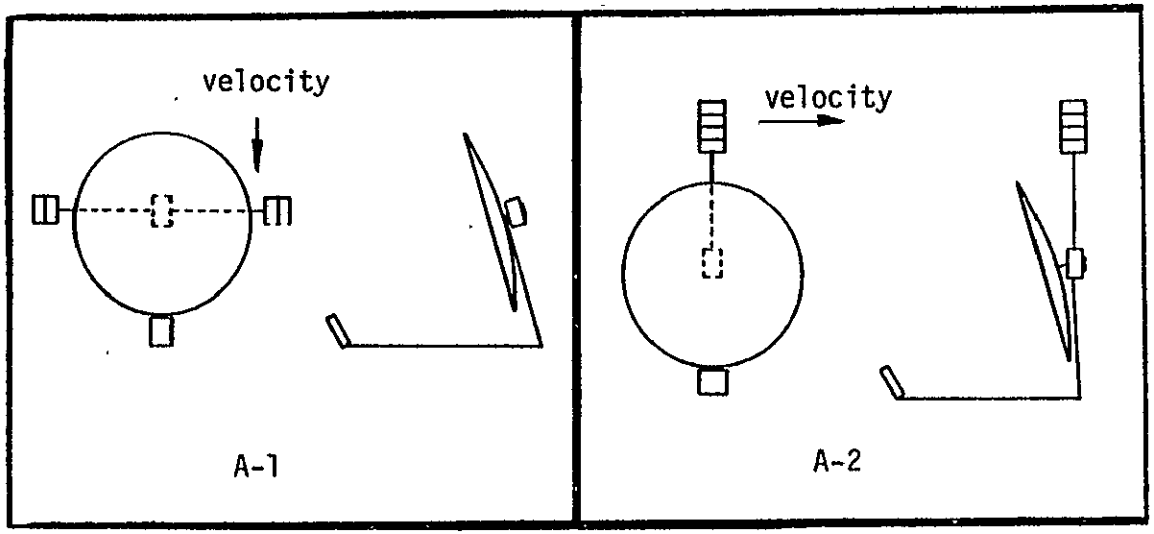


Figure 3-1. Offset Configurations A-1 and A-2 [2]

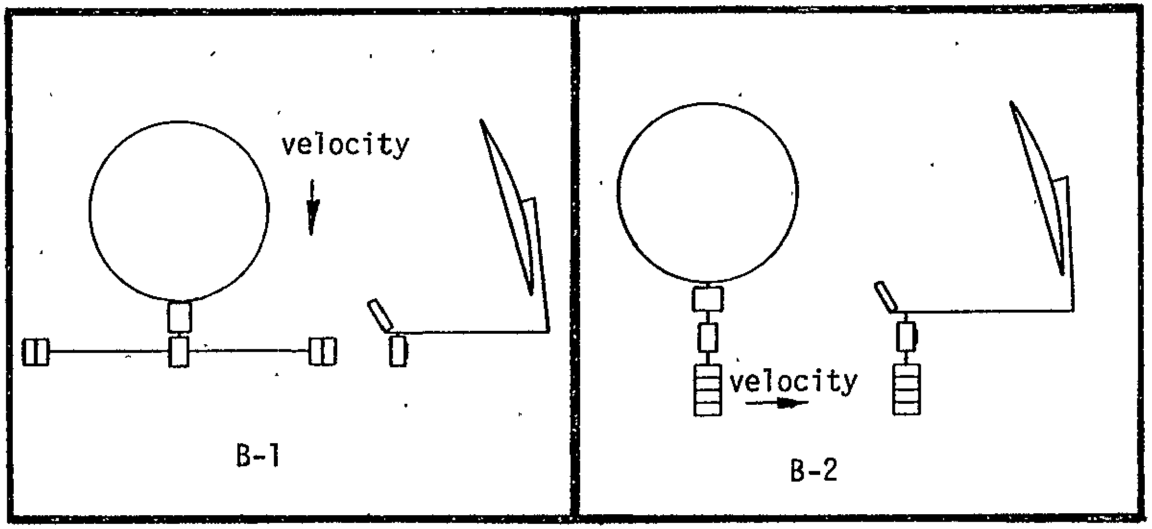


Figure 3-2. Offset Configurations B-1 and B-2 [2]

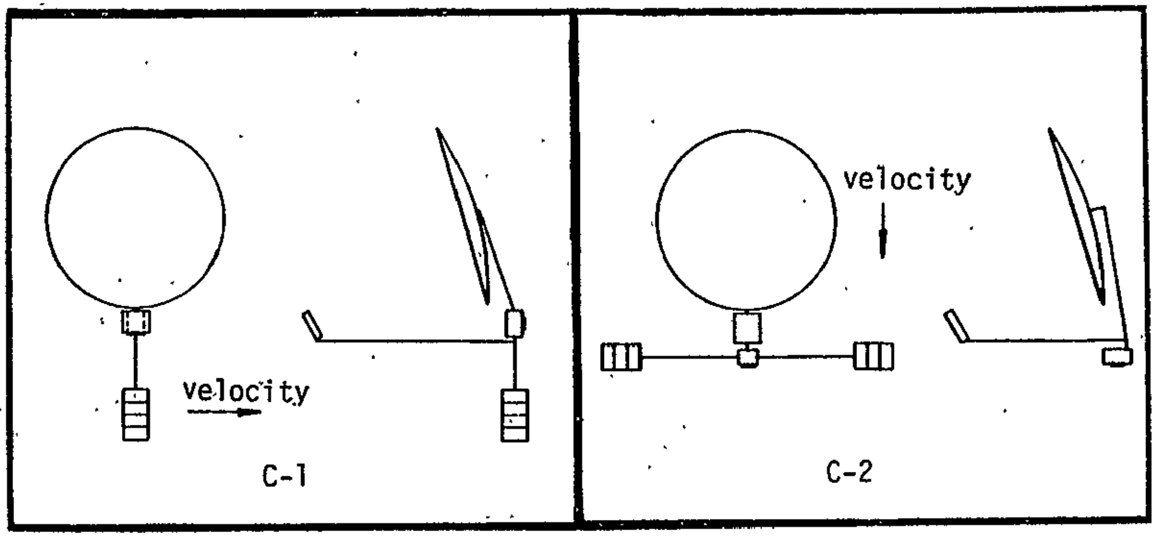


Figure 3-3. Offset Configurations C-1 and C-2 [2]

3.2.1 Orbital Configuration 1

A perspective sketch of configuration 1 (B-1), obtained from [1], is shown in Figure 3-4. The deployed dimensions, also from [1], are depicted in Figure 3-5. In this configuration, the reflector is deployed with its deployment boom in the anti-earth direction. The boom consists of two sections: an offset and a parallel section. The electrical boresight of the antenna is pointed northward to the center of CONUS to provide proper coverage to CONUS, Canada, and Alaska. The reflector is a 20-rib, 20-m wrap-rib antenna designed by Lockheed. The satellite bus shown in these figures is an Advanced Communications Satellite Bus being developed by Ford Aerospace and Communications Corporation (FACC). This bus is a rectangular box which measures 2.6 meters long by 1.7 meters high by 1.6 meters wide [1]. The box is located such that the widest dimension is oriented to look north and south to assure the maximum thermal radiator area available for the payload equipment. The bus consists of a Communications Module and a Subsystem Module. The Communications Module houses the communications transponder equipment located on the north and south panels of the box. Each panel is equipped with heat pipes, and there are Optical Solar Reflectors (OSR) on the outside of the panel to distribute the thermal heat load and control the temperature of the equipment. Areas of the satellite that do not have high thermal power dissipations are covered externally by multi-layer insulating blankets.

The subsystem module supports the housekeeping functions of the spacecraft, which include the bipropellant propulsion system, attitude and orbit control subsystem, the power subsystem, and the telemetry, tracking, and command subsystem.

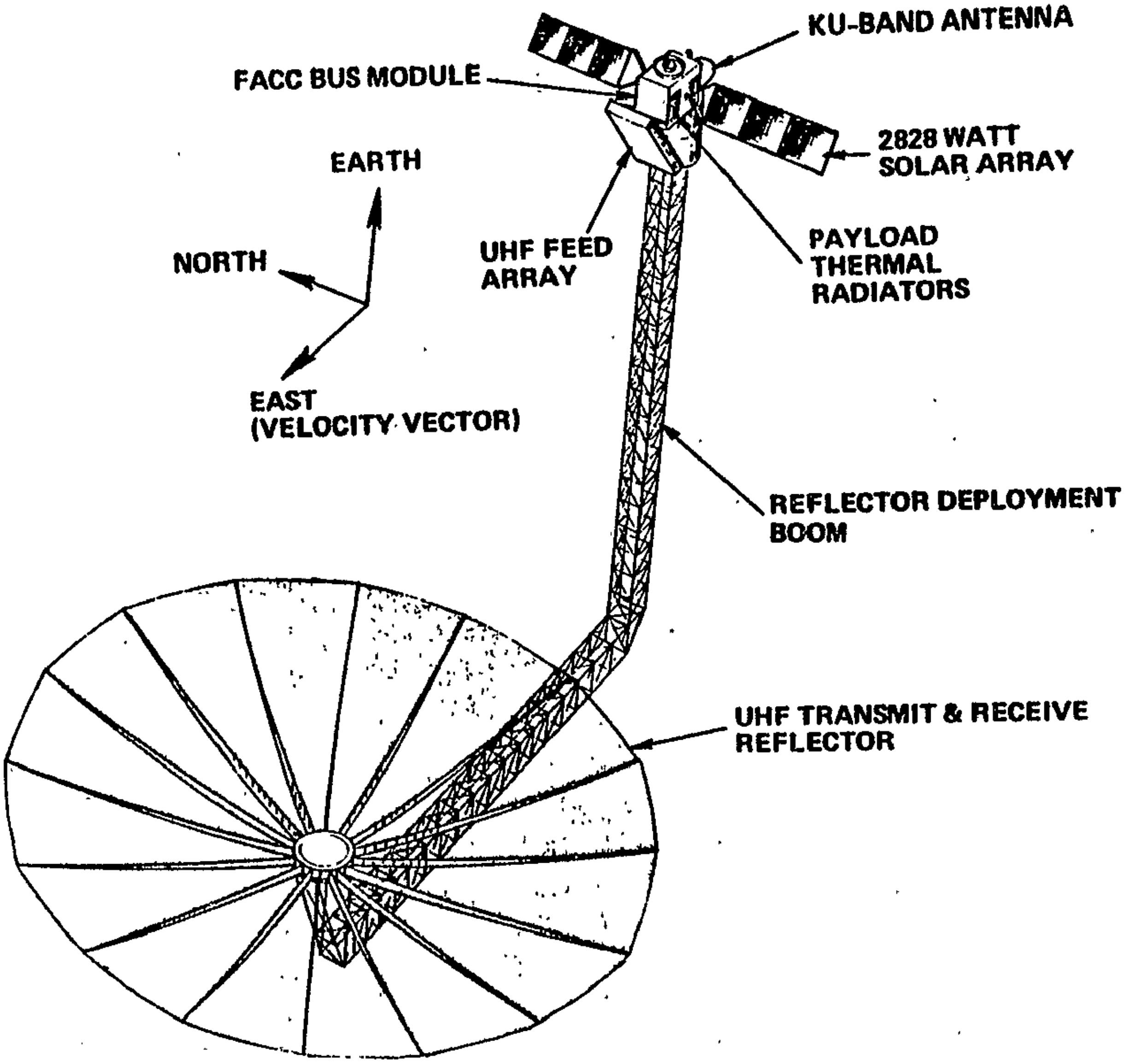


Figure 3-4. A Perspective Sketch of the Spacecraft [1]
(Configuration 1)

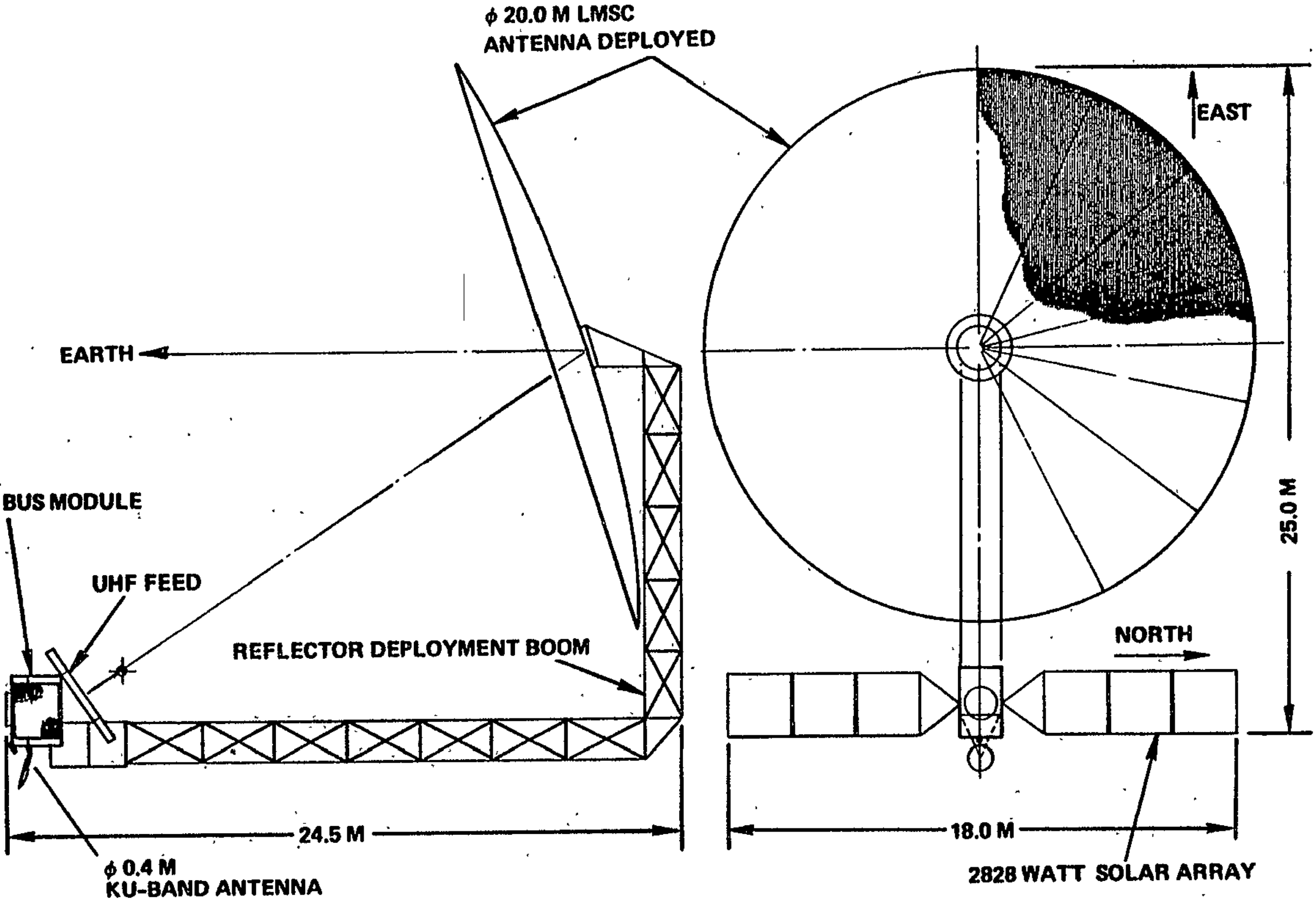


Figure 3-5. Deployed Configuration (Configuration 1) [1]

The antenna feed is mounted on the bus. Because of the large size, a deployable feed is required. This allows the feed to be stowed during launch to reduce the stowed dimension of the spacecraft. After launch, the feed is rotated into position to illuminate the reflector. Because the feed is closely coupled to the payload module, the RF loss is minimized.

The solar array consists of two wings, which are mounted on the north and south panels of the bus. As shown in the figures, each wing consists of three solar panels covered with solar cells, and the wings span a total of 18 meters. (It is noted that the baseline design actually requires four panels for each wing in order to provide the required power. The wings span about 23 meters instead of 18 meters.)

The backhaul antenna which is 0.4 m in diameter is mounted on the west side of the spacecraft bus. The size of the backhaul antenna is relatively insignificant compared to the UHF antenna.

3.2.2 Orbital Configuration 2

An example of the orbital configuration for the second baseline configuration is shown in Figure 3-6 [2]. As previously mentioned, both the reflector and the feed assembly are deployed away from the bus. The feed assembly includes the radiating elements, the immediate supporting structure, the transponder equipment, heat pipes, and radiators. The transponder components are mounted on the inside walls of the north-facing and south-facing panels of the feed assembly. The outside of these panels is covered with thermal radiators. The housekeeping equipment, including TT&C, power subsystem, and propulsion subsystem, are located in the bus. The solar arrays are deployed away from the

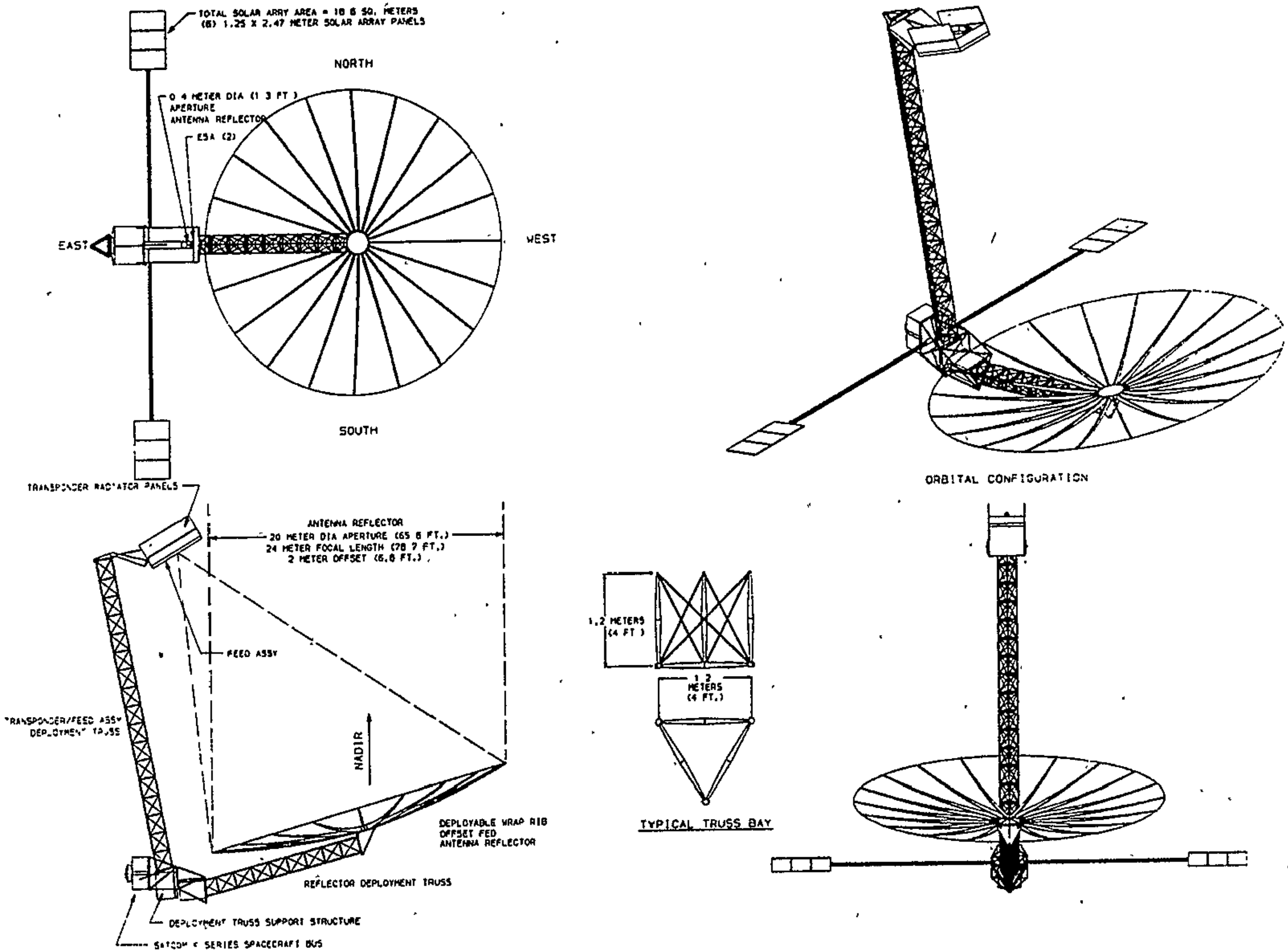


Figure 3-6. On-Orbit Configuration (Configuration 2) [2]

ORIGINAL PAGE IS
OF POOR QUALITY

bus by a long boom more than 10-m long. A long boom is necessary in order to avoid shadowing of the solar array. The orientation of the spacecraft is also shown in Figure 3-6. The satellite bus shown is the Series 4000 satellite bus developed by RCA Astro Electronics [2].

3.3 STOWED CONFIGURATIONS

The 20-m reflector and its supporting structure pose a challenge to the attitude control subsystem as well as the packaging of the spacecraft. Launch cost is determined by the spacecraft weight and the occupied length in the STS cargo bay. It is essential to minimize the stowed length of the spacecraft. The stowed configurations are discussed in the following sections for the two baseline orbital configurations.

3.3.1 Configuration 1

The stowed length in the cargo bay is largely influenced by the stowed dimension of the large reflector. The stowed dimension of the 20-m reflector and its deployment mechanism is estimated by Lockheed to be approximatley 3 m (9.7 ft) in length and 2.8 m (9.2 ft) in diameter. To fit such a large structure into the STS cargo bay requires that the satellite be launched in the horizontal position. Figure 3-7, obtained from [1], shows the stowed configuration of the 20-m satellite. The reflector and its supporting structure are mounted directly onto the FACC bus module central cylinder. The perigee module, which propels the spacecraft into the geostationary orbit from the STS parking orbit, is mounted to the satellite bus and secured to the spacecraft support cradle. The cradle provides the necessary mechanical and electrical interface between the bus and the STS.

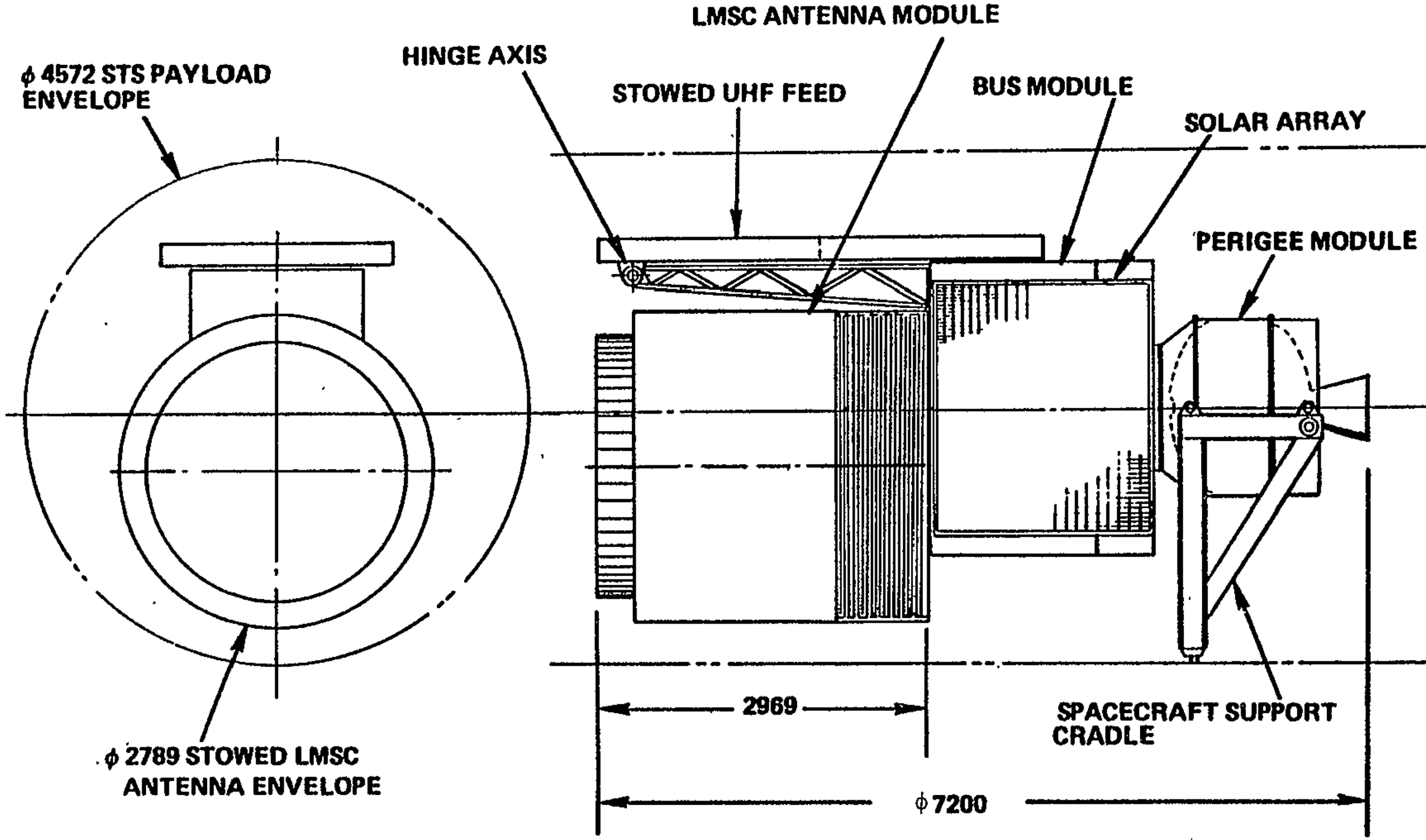


Figure 3-7. The Stowed Configuration (Configuration 1) [2]

ORIGINAL PAGE IS OF POOR QUALITY

The UHF feed is stowed and mounted to the bus. During deployment, the feed assembly will undergo a simple 57-degree rotation about the hinge axis in order to properly illuminate the reflector. The stowed length of the entire spacecraft is about 7.2 m (24 ft).

3.3.2 Configuration 2

Configuration 2 also requires the spacecraft to be launched in a horizontal position. Because this configuration requires two deployment cages, the packaging of this spacecraft in the STS cargo bay is slightly more complex and it requires a longer length. As depicted in Figure 3-8 [2], the dominating components are the reflector, its deployment system, the feed assembly, its deployment system, the satellite bus, SCOTS, and the cradle. The size of the feed assembly is approximately 2 m (6 ft) by 4 m (13 ft). The stowed length of the spacecraft including the perigee stage is approximatley 8.8 m (29 ft).

3.4 LINK BUDGETS

To facilitate the design of the system, it is necessary to establish a link budget. As previously explained, there are three modes of communications, and each of them requires a different budget because the interference environment is different. Using typical parameters, a budget has been established for each of these communications modes, as shown in Tables 3-2, 3-3, and 3-4.

The link tables show that the satellite power required to satisfy a given link performance (i.e., an end-to-end EB/NO of 10.7 dB plus a margin of 2 dB) is -8.3 dBW and -10.21 dBW for the mobile-to-mobile and fixed-station-to-mobile communications, respectively. The difference of 1.9 dB in the power requirement between these two modes of communication creates a design problem, worsening the already serious interference situation by lowering the intermod

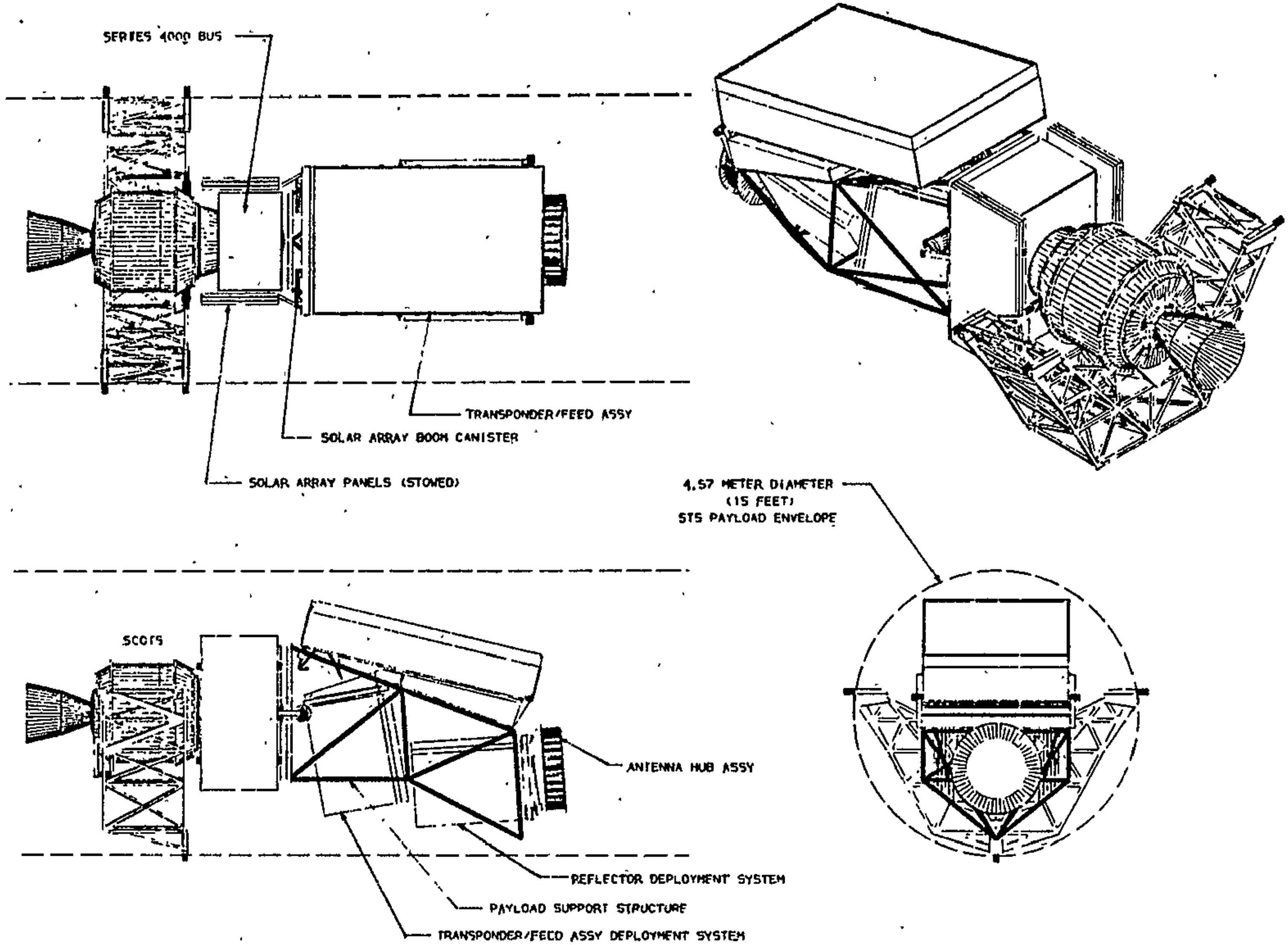


Figure 3-8. The Stowed Configuration (Configuration 2) [2]

ORIGINAL PAGE IS
OF POOR QUALITY

ORIGINAL PAGE IS OF POOR QUALITY

TABLE 3-2. DESIGN CONTROL TABLE FOR MOBILE-TO-MOBILE LINKS (1.5 W/CH)

		MOBILE TO SAT					SAT TO MOBILE				
	PDF	DESIGN	FAV TOL	ADV TOL	MEAN	VAR (X.01)	DESIGN	FAV TOL	ADV TOL	MEAN	VAR (X.01)
TRANSMITTER PARAMETERS	---										
1)XMIT POWER,DBW	TRI	7.00	1.00	0.00	7.33	5.56	-8.30	.50	.50	-8.30	4.17
2)XMIT CIRCUIT LOSS,DB	REC	-1.50	.20	.50	-1.65	4.08	-2.40	.20	1.00	-2.80	12.00
3)ANTENNA GAIN,DBI	TRI	10.00	1.50	0.00	10.50	12.50	42.20	.50	.50	42.20	4.17
4)EIRP,DBW ((1)+(2)+(3))		15.50			16.18		31.50			31.10	
5)POINTING LOSS,DB	TRI	0.00	0.00	0.00	0.00	0.00	-1.00	.30	.50	-1.07	2.72
PATH PARAMETERS											
6)SPACE LOSS,DB		-182.94			-182.94		-183.24			-183.24	
(FREQUENCY,MHZ =		836.00					866.00				)
(RANG= 40000 KM)											
7)ATMOSPHERIC ATTN,DB	TRI	0.00	0.00	.10	-.03	.06	0.00	0.00	.10	-.03	.06
8)E.O.B.LOSS,DB	TRI	-4.00	0.00	.50	-4.17	1.39	-4.00	0.00	.50	-4.17	1.39
9)MULTIPATH LOSS,DB	GAU(1)	-5.00	2.00	0.00	-4.00	11.11	-5.00	2.00	0.00	-4.00	11.11
10)SHADOWING LOSS,DB	DEL(2)	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	
RECEIVER PARAMETERS											
11)POLARIZATION LOSS,DB	TRI	-.50	.10	.10	-.50	.17	-.50	.10	.10	-.50	.17
12)ANTENNA GAIN,DBI	TRI	41.60	.50	.50	41.60	4.17	10.00	1.50	0.00	10.50	12.50
13)POINTING LOSS,DB	TRI	-1.00	.30	.50	-1.07	2.72	0.00	0.00	0.00	0.00	0.00
14)RECEIVED SIGNAL POWER,DBW		-136.34			-134.92		-152.24			-151.41	
(SUM OF LINES 4 - 13)											
15)SYSTEM TEMPERATURE,DBK	GAU(3)	29.22	.90	1.30			27.06	.20	.40		
(CIRCUIT LOSS,DB =		-2.40	.20	1.00			-1.50	.20	.20		)
(RCVR N.F. ,DB =		2.20	.70	.30			1.50	0.00	.20		)
(ANTENNA TEMP,K =		290.00	0.00	0.00			220.00	0.00	0.00		)
16)RECEIVED NO,DBW/HZ	GAU(4)	-199.38	.90	1.30	-199.58	13.44	-201.54	.20	.40	-201.64	1.00
((15)-228.6 DBW/HZ)											
(BANDWIDTH,KHZ =		5.00					5.00				)
CHANNEL PERFORMANCE											
17)RCVD C/NO,DB-HZ ((14)-(16))		63.04			64.66		49.29			50.23	
18)EFFECTIVE C/NO,DB-HZ		56.03			56.30		46.50			47.00	
(OVERALL C/I,DB =	GAU(5)						12.96	.95	.95	12.95	10.04)
(INTERBEAM ISOLATION =	TRI	20.00	1.00	1.00	20.00	16.67	20.00	1.00	1.00	20.00	)
(INTERSAT. ISOLATION =							23.00	.50	.50	23.00	)
(INTERMOD ISOLATION =							24.00	1.00	1.00	24.00	)
(TURNAROUND C/NO =	GAU						63.04			64.66	55.19)
(NO(UP)/NO(REQUIRED) =		.15					.15				)
(MODEM LOSS,DB =		0.00			0.00		0.00			0.00	)
19)REQUIRED C/NO,DB-HZ		52.74			52.74		44.50			44.50	
20)PERFORMANCE MARGIN,DB		3.29			3.56	.85	2.00			2.50	1.07
((18)-(19))						(1 SIG)					(1 SIG)

NOTES: (1) WITHOUT BLOCKAGE/SHADOWING,5 DB SHOULD BE SUFFICIENT 99% OF THE TIME BASED ON RECENT EXPERIMENTAL DATA.

(2) ASSUME NO BLOCKAGE/SHADOWING.

(3) -(5) TOLERANCES ARE CALCULATED BY PROGRAM.

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE 3-3. DESIGN CONTROL TABLE FOR FIXED-STATION-TO-MOBILE (FORWARD) LINKS (.1 W/CH)

		GATEWAY TO SAT					SAT TO MOBILE				
	PDF	DESIGN	FAV TOL	ADV TOL	MEAN	VAR (X.01)	DESIGN	FAV TOL	ADV TOL	MEAN	VAR (X.01)
TRANSMITTER PARAMETERS	---										
1)XMIT POWER,DBW	TRI	-1.07	1.00	.50	-.90	9.72	-10.22	.50	.50	-10.22	4.17
2)XMIT CIRCUIT LOSS,DB	REC	-2.00	.50	.50	-2.00	8.33	-2.40	.20	1.00	-2.80	12.00
3)ANTENNA GAIN,DBI	TRI	49.60	1.00	1.00	49.60	16.67	42.20	.50	.50	42.20	4.17
4)EIRP,DBW ((1)+(2)+(3))		46.53			46.70		29.58			29.18	
5)POINTING LOSS,DB	TRI	-.50	0.00	.50	-.67	1.39	-1.00	.30	.50	-1.07	2.72
PATH PARAMETERS											
6)SPACE LOSS,DB		-206.90			-206.90		-183.24			-183.24	
(FREQUENCY,GHZ/MHZ =		13.20					866.00				)
(RANG= 40000 KM)											
7)ATMOSPHERIC ATTN,DB	TRI	-1.10	.10	.10	-1.10	.17	0.00	0.00	.10	-.03	.06
8)E.O.B.LOSS,DB	TRI	-4.00	0.00	.50	-4.17	1.39	-4.00	0.00	.50	-4.17	1.39
9)MULTIPATH LOSS,DB	GAU(1)	0.00	0.00	0.00	0.00	0.00	-5.00	2.00	0.00	-4.00	11.11
10)SHADOWING LOSS,DB	DEL(2)	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	
RECEIVER PARAMETERS											
11)POLARIZATION LOSS,DB	TRI	0.00	0.00	.10	-.03	.06	-.50	.10	.10	-.50	.17
12)ANTENNA GAIN,DBI	TRI	32.30	.50	.50	32.30	4.17	10.00	1.50	0.00	10.50	12.50
13)POINTING LOSS,DB	TRI	-.50	.20	.20	-.50	.67	0.00	0.00	0.00	0.00	0.00
14)RECEIVED SIGNAL POWER,DBW		-134.17			-134.37		-154.16			-153.33	
(SUM OF LINES 4 - 13)											
15)SYSTEM TEMPERATURE,DBK	GAU(3)	29.12	.60	.90			27.06	.20	.40		
(CIRCUIT LOSS,DB =		-1.50	.10	.40			-1.50	.20	.20		)
(RCVR N.F. ,DB =		3.00	.50	.50			1.50	0.00	.20		)
(ANTENNA TEMP,K =		290.00	0.00	0.00			220.00	0.00	0.00		)
16)RECEIVED NO,DBW/HZ	GAU(4)	-199.48	.60	.90	-199.63	6.25	-201.54	.20	.40	-201.64	1.00
((15)-228.6 DBW/HZ)											
(BANDWIDTH,KHZ =		5.00					5.00				)
CHANNEL PERFORMANCE											
17)RCVD C/NO,DB-HZ ((14)-(16))		65.30			65.25		47.37			48.31	
18)EFFECTIVE C/NO,DB-HZ		63.05	.38	.43	63.03		46.50			47.24	
(OVERALL C/I,DB =	GAU(5)						17.21	.86	.87	17.21	8.37)
(INTERBEAM ISOLATION =							20.00	1.00	1.00	20.00	)
(INTERSAT. ISOLATION =							23.00	.50	.50	23.00	)
(INTERMOD ISOLATION =	TRI	30.00	1.00	1.00	30.00	16.67	24.00	1.00	1.00	24.00	)
(TURNAROUND C/NO =	GAU						65.30			65.25	48.81)
(NO(UP)/NO(REQUIRED) =		.05					.05				)
(MODEM LOSS,DB =		0.00			0.00		0.00			0.00	)
19)REQUIRED C/NO,DB-HZ		57.51			57.51		44.50			44.50	
20)PERFORMANCE MARGIN,DB ((18)-(19))		5.54			5.51	.81 (1 SIG)	2.00			2.74	1.03 (1 SIG)

NOTES (1)-(5): SEE TABLE 3-2.

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE 3-4. DESIGN CONTROL TABLE FOR MOBILE-TO-FIXED-STATION (RETURN) LINKS (BASELINE)

		MOBILE TO SAT					SAT TO GATEWAY				
	PDF	DESIGN	FAV TOL	ADV TOL	MEAN	VAR (X.01)	DESIGN	FAV TOL	ADV TOL	MEAN	VAR (X.01)
TRANSMITTER PARAMETERS	---										
1)XMIT POWER,DBW	TRI	7.00	1.00	0.00	7.33	5.56	-21.88	.50	.50	-21.88	4.17
2)XMIT CIRCUIT LOSS,DB	REC	-1.50	.20	.50	-1.65	4.08	-1.50	.10	.40	-1.65	2.08
3)ANTENNA GAIN,DBI	TRI	10.00	1.50	0.00	10.50	12.50	31.20	.50	.50	31.20	4.17
4)EIRP,DBW ((1)+(2)+(3))		15.50			16.18		7.82			7.67	
5)POINTING LOSS,DB	TRI	0.00	0.00	0.00	0.00	0.00	-.50	.20	.20	-.50	.67
PATH PARAMETERS											
6)SPACE LOSS,DB		-182.94			-182.94		-205.82			-205.82	
(FREQUENCY,MHZ/GHZ =		836.00					11.65				)
(RANGE= 40000 KM)											
7)ATMOSPHERIC ATTN,DB	TRI	0.00	0.00	.10	-.03	.06	-.90	.10	.10	-.90	.17
8)E.O.B.LOSS,DB	TRI	-4.00	0.00	.50	-4.17	1.39	-4.00	0.00	.50	-4.17	1.39
9)MULTIPATH LOSS,DB	GAU(1)	-5.00	2.00	0.00	-4.00	11.11	0.00	0.00	0.00	0.00	0.00
10)SHADOWING LOSS,DB	DEL(2)	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	
RECEIVER PARAMETERS											
11)POLARIZATION LOSS,DB	TRI	-.50	.10	.10	-.50	.17	0.00	0.00	.10	-.03	.06
12)ANTENNA GAIN,DBI	TRI	41.60	.50	.50	41.60	4.17	48.90	1.00	1.00	48.90	16.67
13)POINTING LOSS,DB	TRI	-1.00	.30	.50	-1.07	2.72	-.50	0.00	.50	-.67	1.39
14)RECEIVED SIGNAL POWER,DBW		-136.34			-134.92		-155.00			-155.51	
(SUM OF LINES 4 - 13)											
15)SYSTEM TEMPERATURE,DBK	GAU(3)	29.22	.90	1.30			25.30	.50	.60		
(CIRCUIT LOSS,DB =		-2.40	.20	1.00			-1.00	0.00	.40		)
(RCVR N.F. ,DB =		2.20	.70	.30			2.00	.50	.20		)
(ANTENNA TEMP,K =		290.00	0.00	0.00			50.00	0.00	0.00		)
16)RECEIVED NO,DBW/HZ	GAU(4)	-199.38	.90	1.30	-199.58	13.44	-203.30	.50	.60	-203.35	3.36
((15)-228.6 DBW/HZ)											
(BANDWIDTH,KHZ =		5.00					5.00				)
CHANNEL PERFORMANCE											
17)RCVD C/NO,DB-HZ ((14)-(16))		63.04			64.66		48.31			47.84	
18)EFFECTIVE C/NO,DB-HZ		56.03			56.30		46.50			46.21	
(OVERALL C/I,DB =	GAU(5)						14.49	1.00	1.00	14.49	11.11)
(INTERBEAM ISOLATION =	TRI	20.00	1.00	1.00	20.00	16.67					)
(INTERSAT. ISOLATION =											)
(INTERMOD ISOLATION =							24.00	1.00	1.00	24.00	)
(TURNAROUND C/NO =	GAU						63.04			64.66	55.19)
(NO(UP)/NO(REQUIRED) =		.15					.15				)
(MODEM LOSS,DB =		0.00			0.00		0.00			0.00	)
19)REQUIRED C/NO,DB-HZ		52.74			52.74		44.50			44.50	
20)PERFORMANCE MARGIN,DB		3.29			3.56	.85	2.00			1.71	1.00
((18)-(19))						(1 SIG)					(1 SIG)

NOTES (1)-(5): SEE TABLE 3-2.

isolation from 24 dB to 22.1 dB, and the interbeam isolation from 20 to 18.1 dB. Serious performance degradation would occur. To alleviate this problem, the per-channel power for both the mobile-to-mobile and fixed-station-to-mobile communication has been fixed at -8.89 dBW, corresponding to 0.129 watts per channel. The resulting link margin is 3.05 dB and 1.68 dB for the fixed-station-to-mobile and the mobile-to-mobile communications, respectively (see Tables 3-5 and 3-6). Since mobile-to-mobile traffic is expected to be a small percentage of the total traffic, a lower link margin is acceptable.

The satellite power required for the mobile-to-fixed-station traffic is 0.0065 watts per channel, with a link margin of 2 dB.

A brief description of the major link parameters is given in the following section.

3.4.1 Required EB/NO

The requirement on EB/NO is driven by the required quality of service. As described in Chapter 1, MSAT-2 is designed to provide both voice and data services. Voice service is assumed to be digitized using linear predictive coding (LPC). The acceptable bit error rate (BER) is on the order of 10^{-3}, which corresponds to an EB/NO of about 10.7 dB, based on results of the channel simulator using the baseline modulation scheme, GMSK, with coherent detection.(It is noted that two-bit differential detection is the current baseline for MSAT-X.) For a given BER, the required EB/NO varies over a few dB depending on the modulation/ demodulation scheme. While efforts are being taken to select a suitable scheme for the mobile satellite system, it is

TABLE 3-5. DESIGN CONTROL TABLE FOR MOBILE-TO-MOBILE LINKS (BASELINE,.13 W/CH)

		M O B I L E	T O	S A T			S A T	T O	M O B I L E		
	PDF	DESIGN	FAV TOL	ADV TOL	MEAN	VAR (X.01)	DESIGN	FAV TOL	ADV TOL	MEAN	VAR (X.01)
TRANSMITTER PARAMETERS	---										
1)XMIT POWER,DBW	TRI	7.00	1.00	0.00	7.33	5.56	-8.89	.50	.50	-8.89	4.17
2)XMIT CIRCUIT LOSS,DB	REC	-1.50	.20	.50	-1.65	4.08	-2.40	.20	1.00	-2.80	12.00
3)ANTENNA GAIN,DBI	TRI	10.00	1.50	0.00	10.50	12.50	42.20	.50	.50	42.20	4.17
4)EIRP,DBW ((1)+(2)+(3))		15.50			16.18		30.91			30.51	
5)POINTING LOSS,DB	TRI	0.00	0.00	0.00	0.00	0.00	-1.00	.30	.50	-1.07	2.72
PATH PARAMETERS											
6)SPACE LOSS,DB		-182.94			-182.94		-183.24			-183.24	
(FREQUENCY,MHZ =		836.00					866.00				)
(RANG= 40000 KM)											
7)ATMOSPHERIC ATTN,DB	TRI	0.00	0.00	.10	-.03	.06	0.00	0.00	.10	-.03	.06
8)E.O.B.LOSS,DB	TRI	-4.00	0.00	.50	-4.17	1.39	-4.00	0.00	.50	-4.17	1.39
9)MULTIPATH LOSS,DB	GAU(1)	-5.00	2.00	0.00	-4.00	11.11	-5.00	2.00	0.00	-4.00	11.11
10)SHADOWING LOSS,DB	DEL(2)	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	
RECEIVER PARAMETERS											
11)POLARIZATION LOSS,DB	TRI	-.50	.10	.10	-.50	.17	-.50	.10	.10	-.50	.17
12)ANTENNA GAIN,DBI	TRI	41.60	.50	.50	41.60	4.17	10.00	1.50	0.00	10.50	12.50
13)POINTING LOSS,DB	TRI	-1.00	.30	.50	-1.07	2.72	0.00	0.00	0.00	0.00	0.00
14)RECEIVED SIGNAL POWER,DBW		-136.34			-134.92		-152.83			-152.00	
(SUM OF LINES 4 - 13)											
15)SYSTEM TEMPERATURE,DBK	GAU(3)	29.22	.90	1.30			27.06	.20	.40		
(CIRCUIT LOSS,DB =		-2.40	.20	1.00			-1.50	.20	.20		)
(RCVR N.F. ,DB =		2.20	.70	.30			1.50	0.00	.20		)
(ANTENNA TEMP,K =		290.00	0.00	0.00			220.00	0.00	0.00		)
16)RECEIVED NO,DBW/HZ	GAU(4)	-199.38	.90	1.30	-199.58	13.44	-201.54	.20	.40	-201.64	1.00
((15)-228.6 DBW/HZ)											
(BANDWIDTH,KHZ =		5.00					5.00				)
CHANNEL PERFORMANCE											
17)RCVD C/NO,DB-HZ ((14)-(16))		63.04			64.66		48.70			49.64	
18)EFFECTIVE C/NO,DB-HZ		56.03			56.30		46.18			46.71	
(OVERALL C/I,DB =	GAU(5)						12.96	.95	.95	12.95	10.04)
(INTERBEAM ISOLATION =	TRI	20.00	1.00	1.00	20.00	16.67	20.00	1.00	1.00	20.00	)
(INTERSAT. ISOLATION =							23.00	.50	.50	23.00	)
(INTERMOD ISOLATION =							24.00	1.00	1.00	24.00	)
(TURNAROUND C/NO =	GAU						63.04			64.66	55.19)
(NO(UP)/NO(REQUIRED) =		.15					.15				)
(MODEM LOSS,DB =		0.00			0.00		0.00			0.00	)
19)REQUIRED C/NO,DB-HZ		52.74			52.74		44.50			44.50	
20)PERFORMANCE MARGIN,DB		3.29			3.56	.85 (1 SIG)	1.68			2.21	1.07 (1 SIG)
((18)-(19))											

NOTES (1)-(5): SEE TABLE 3-2.

TABLE 3-6. DESIGN CONTROL TABLE FOR FIXED-STATION-TO-MOBILE (FORWARD) LINKS (BASELINE, .13 W/CH)

		GATEWAY TO SAT					SAT TO MOBILE				
	PDF	DESIGN	FAV TOL	ADV TOL	MEAN	VAR (X.01)	DESIGN	FAV TOL	ADV TOL	MEAN	VAR (X.01)
TRANSMITTER PARAMETERS	---										
1)XMIT POWER,DBW	TRI	-1.07	1.00	.50	-.90	9.72	-8.89	.50	.50	-8.89	4.17
2)XMIT CIRCUIT LOSS,DB	REC	-2.00	.50	.50	-2.00	8.33	-2.40	.20	1.00	-2.80	12.00
3)ANTENNA GAIN,DBI	TRI	49.60	1.00	1.00	49.60	16.67	42.20	.50	.50	42.20	4.17
4)EIRP,DBW ((1)+(2)+(3))		46.53			46.70		30.91			30.51	
5)POINTING LOSS,DB	TRI	-.50	0.00	.50	-.67	1.39	-1.00	.30	.50	-1.07	2.72
PATH PARAMETERS											
6)SPACE LOSS,DB		-206.90			-206.90		-183.24			-183.24	
(FREQUENCY,GHZ/MHZ =		13.20					866.00				)
(RANG= 40000 KM)											
7)ATMOSPHERIC ATTN,DB	TRI	-1.10	.10	.10	-1.10	.17	0.00	0.00	.10	-.03	.06
8)E.O.B.LOSS,DB	TRI	-4.00	0.00	.50	-4.17	1.39	-4.00	0.00	.50	-4.17	1.39
9)MULTIPATH LOSS,DB	GAU(1)	0.00	0.00	0.00	0.00	0.00	-5.00	2.00	0.00	-4.00	11.11
10)SHADOWING LOSS,DB	DEL(2)	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	
RECEIVER PARAMETERS											
11)POLARIZATION LOSS,DB	TRI	0.00	0.00	.10	-.03	.06	-.50	.10	.10	-.50	.17
12)ANTENNA GAIN,DBI	TRI	32.30	.50	.50	32.30	4.17	10.00	1.50	0.00	10.50	12.50
13)POINTING LOSS,DB	TRI	-.50	.20	.20	-.50	.67	0.00	0.00	0.00	0.00	0.00
14)RECEIVED SIGNAL POWER,DBW		-134.17			-134.37		-152.83			-152.00	
(SUM OF LINES 4 - 13)											
15)SYSTEM TEMPERATURE,DBK	GAU(3)	29.12	.60	.90			27.06	.20	.40		
(CIRCUIT LOSS,DB =		-1.50	.10	.40			-1.50	.20	.20		)
(RCVR N.F. ,DB =		3.00	.50	.50			1.50	0.00	.20		)
(ANTENNA TEMP,K =		290.00	0.00	0.00			220.00	0.00	0.00		)
16)RECEIVED NO,DBW/HZ	GAU(4)	-199.48	.60	.90	-199.63	6.25	-201.54	.20	.40	-201.64	1.00
((15)-228.6 DBW/HZ)											
(BANDWIDTH,KHZ =		5.00					5.00				)
CHANNEL PERFORMANCE											
17)RCVD C/NO,DB-HZ ((14)-(16))		65.30			65.25		48.70			49.64	
18)EFFECTIVE C/NO,DB-HZ		63.05	.38	.43	63.03		47.55			48.25	
(OVERALL C/I,DB =	GAU(5)						17.21	.86	.87	17.21	8.37)
(INTERBEAM ISOLATION =							20.00	1.00	1.00	20.00	)
(INTERSAT. ISOLATION =							23.00	.50	.50	23.00	)
(INTERMOD ISOLATION =	TRI	30.00	1.00	1.00	30.00	16.67	24.00	1.00	1.00	24.00	)
(TURNAROUND C/NO =	GAU						65.30			65.25	48.81)
(NO(UP)/NO(REQUIRED) =		.05					.05				)
(MODEM LOSS,DB =		0.00			0.00		0.00			0.00	)
19)REQUIRED C/NO,DB-HZ		57.51			57.51		44.50			44.50	
20)PERFORMANCE MARGIN,DB		5.54			5.51	.81	3.05			3.75	1.03
((18)-(19))						(1 SIG)					(1 SIG)

NOTES (1)-(5): SEE TABLE 3-2.

assumed that an EB/NO of 10.7 dB will be sufficient for a BER of 10^{-3}. The required BER for the data service is in the neighborhood of 10^{-6}. Without the benefit of coding, this would require an EB/NO of about 15 dB. The per-channel power requirement, consequently, would be significantly higher for the data service. The disparity in the per-channel power would, as previously mentioned, worsen the already serious interference environment. To avoid these problems, the required EB/NO for both the LPC voice and the data services is set at 10.7 dB. The 10.7-dB EB/NO will provide an acceptable BER for the voice service as previously mentioned. In order to obtain a BER of 10^{-6} for the data service, coding will have to be employed, and mobile terminals providing such a service will have to be equipped with some sort of decoder, such as a convolutional decoder, which could have a coding gain of 4 to 6 dB.

3.4.2 Antenna Gain

Two antennas are employed by the satellite to support the service and backhaul links. The service link antenna operating at the high UHF is a 20-m antenna. The designed boresight gain of this antenna is 42.3 dB and 42.9 dB for receive and transmit, respectively. Allowing 0.4 dB to account for scan loss and 0.3 dB for the beam-forming network loss, the available gain is 41.6 dB for receive and 42.2 dB for transmit.

The backhaul antenna is a 0.4-m parabolic antenna. The boresight gain of the antenna is 32.3 dB for receive and 31.2 dB for transmit.

The antenna for the mobile terminal is an MGA which is expected to provide a gain of 10 to 12 dB with a minimum of 10 dB for the range of elevation angles expected for mobile terminals located in CONUS. For the northern part of Canada and Alaska, a specially designed antenna may be necessary to provide a 10-dB gain.

3.4.3 Transmitter Circuit Loss

The transmitter circuit loss for the satellite is budgeted as follows: 2.4 dB for the UHF and 1.5 dB for the Ku-band. The 1.5-dB loss for the Ku transmitter is composed of the diplexer loss of 1.0 dB, diplexer connector loss of 0.2 dB, and waveguide loss of 0.3 dB. The loss for the UHF transmitter includes a 1.0-dB loss for the diplexer, 1.2 dB for the coaxial cables, and 0.2 dB for the diplexer connector, giving a total of a 2.4-dB loss. Waveguides are less lossy than coaxial cables. Cables, however, have the advantage of being flexible, and are lighter, smaller, and easier to implement. The baseline design utilizes waveguides for the connection between the Ku-band antenna and the diplexer, and coaxial cables between the UHF feed elements and the diplexers. This is the reason why the UHF transmitter is lossier.

The transmitter circuit loss is assumed to be 1.5 dB for the mobile terminals and 2.0 dB for the gateway. A larger loss for the gateway is acceptable because the loss can easily be made up by increasing the transmitted power. The same does not hold for the mobile terminal for two reasons. First, the transmitter power for a mobile terminal cannot be readily increased as with the gateway or base stations. Secondly, even if more power is available for the mobile transmitter, the additional power would probably be best utilized to increase the link margin, or to reduce the burden on the satellite.

3.4.4 Receiver Circuit Loss

The receiver circuit loss for the satellite is 2.4 dB for the UHF receiver and 1.5 dB for the Ku-band receiver. The 2.4 dB loss for the UHF receiver is made up of a diplexer loss (1.0 dB), cable loss (1.2 dB), and diplexer connector loss (0.2 dB). The Ku-band receiver loss consists of 1.0 dB for

the diplexer, 0.3 dB for the waveguide, and 0.2 dB for the diplexer connector. Similar to the transmitter, the loss of the UHF receiver is higher than the loss of the Ku-band receiver.

The receiver circuit loss for the mobile terminals, the base stations, and the gateway stations is assumed to be 1.5 dB.

3.4.5 Receiver Noise Figure

The noise figure for the UHF receiver on-board the satellite is 2.2 dB. For the backhaul receiver, a higher noise figure (3.0 dB) is assumed because the higher noise figure can easily be compensated for.

The noise figure for the mobile terminal is assumed to be 1.5 dB. Based on work performed by MSAT-X, noise figures in the range of 1.58 dB to 1.60 dB were measured [4]. With further improvement, a mobile receiver having a 1.5-dB noise figure is judged to be achievable and affordable with the 1990 technology.

The backhaul link is not as severely constrained as the UHF link; the noise figure requirement can be slightly relaxed. Based on current technologies, a 2.0-dB noise figure is assumed for the gateway stations and base stations.

3.4.6 Antenna Temperature

The temperature of the earth-looking UHF and Ku-band antennas is assumed to be 290°K. The temperature of the mobile antenna is 180°K, and of the gateway station/base station is 50°K [3].

3.4.7 Intermodulation Isolation and Intersatellite Isolation

The achievable intermodulation isolation and intersatellite isolation are 24 and 23 dB, respectively, as indicated in Sections 2.8.4 and 2.8.5.

3.4.8 Multipath Fading

Thermal noise and interference are not the only impairments on the communications links of a mobile satellite system. Multipath fading can have a significant impact on the design of the system. The extent of multipath fading, however, is one of the least-known parameters. Analyses and experimental results by various individuals and organizations have indicated a signal degradation of varying degrees depending on many variables, including elevation angle, terrain, and the type of mobile antenna. While investigations to better understand and characterize multipath fading are currently being conducted, 5 dB is allocated for the MSAT-2 link budget. According to Vogel and Smith [5], the probability for a signal degradation of 5 dB or less is about 85% for an elevation angle of 15 to 20 degrees, based on limited measurements. Multipath/fading generally improves at higher elevation angles. More on propagation in the mobile satellite environment is presented in Appendix F.

3.4.9 Antenna Pointing Loss

The loss due to the antenna pointing error is made negligible for the UHF antenna by properly designing the pointing system and the antenna feed. The satellite control subsystem is capable of pointing the 20-m antenna with an accuracy of 0.15 degrees or better, which is about one-eighth of the 3-dB beamwidth. The feed is designed such that the area illuminated by the multibeam antenna is slightly larger than the area served. Consequently, a small pointing error of 0.15 degrees will not move the beam outside the coverage area and no loss will occur (see Section 2.6.6). To account for pointing stability, a loss of 1 dB is assumed.

The pointing accuracy for the backhaul antenna is 0.1 degrees or better. A loss of 0.5 dB is allocated in the link budget. Similarly the pointing loss for the gateway stations and the base stations is 0.5 dB. For the mobile terminals, the pointing loss has been included in the antenna gain.

3.4.10 Polarization Loss

Polarization loss is the loss due to the mismatch between the polarization of the transmitting and receiving antennas. A loss of 0.5 dB is allocated for both the service and backhaul links.

3.4.11 Edge-Of-Beam Loss

The gain of the antenna discussed in Section 3.4.2 is the gain at the center of the beam. At the edge of the beam, the gain is reduced. A reduction of 4 dB is allocated for the UHF link (see Chapter 2).

The edge-of-beam loss for the backhaul is also assumed to be 4 dB.

3.4.12 Atmospheric Loss

Atmospheric loss is negligible at UHF. For the backhaul, the loss is estimated to be 1.5 dB and 0.9 dB for uplink and downlink, respectively.

3.5 TRANSPONDER DESIGN

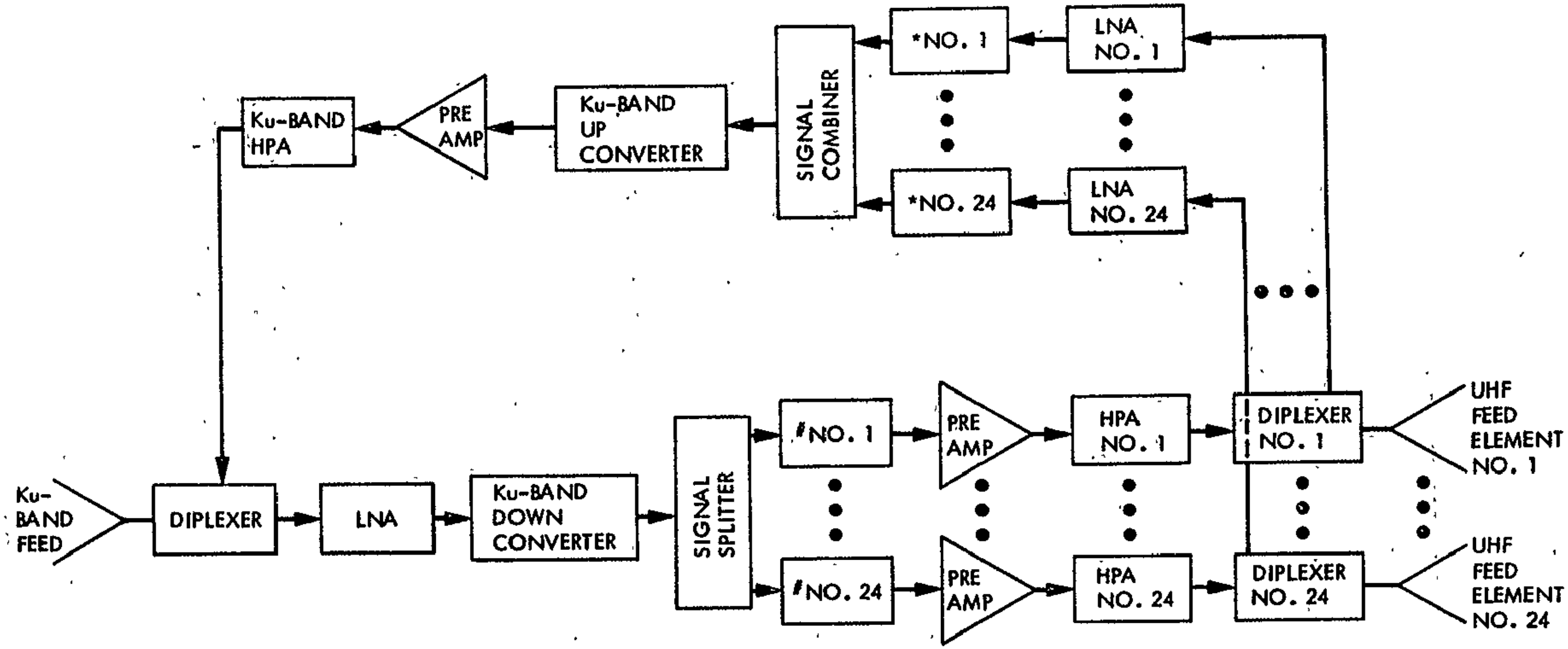
The transponder is designed to receive and transmit in both the UHF and Ku-band frequencies. The UHF uplink signals are received via the multiple UHF beams. They are then amplified, up-converted to 200-MHz IF, and multiplexed into a composite IF signal according to the frequency plan discussed in Section 3.11. The composite IF signal is then up-converted to Ku-band, and

retransmitted to earth using the Ku-band antenna. Conversely, the Ku-band uplink signals are received via the Ku-band antenna. These signals are first down-converted to UHF according to the plan described in Section 3.11. The UHF signals are then amplified and transmitted. A block diagram of the transponder is shown in Figure 3-9 for the east satellite.

The transponder in Figure 3-9 provides mobile-to-mobile, fixed-station-to-mobile, and mobile-to-fixed-station communications. It, however, does not provide a Ku-band cross trap for fixed-station-to-fixed-station communications, i.e., NMC to gateway, and vise versa. The communications between NMC and gateway stations are assumed to be terrestrial links in the baseline design. If a Ku-band cross trap is needed, the block diagram in Figure 3-9 will have to be modified and the required Ku-band bandwidth increased.

3.5.1 Receiver

The transponder has a Ku-band receiver, and a number of UHF receivers. The nonoverlapping feed design normally requires one receiver for each UHF beam. Due to the split-band assumption (see Figure 1-10) an additional receiver is needed for each beam operating in the split subband. The number of receivers thus is larger than the number of multiple beams by an amount equal to the number of reuse of the split subband. For design purposes, this issue is ignored and the number of receivers will be taken as the same as the number of beams. Consequently, there will be 24 receivers for the east satellite, and 21 for the west satellite.



LEGEND
* UPLINK UHF RECEIVER/FREQUENCY TRANSLATOR
\# DOWNLINK RECEIVER/FREQUENCY TRANSLATOR

Figure 3-9. A Simplified Transponder Block Diagram (East Satellite)

A block diagram for the UHF and Ku-band receiver/translator [2] is shown in Figure 3-10. The noise figure is 3 dB for the Ku-band receiver, and 2.2 dB for the UHF receivers. The required technology for the receiver components is shown in Table 3-7.

3.5.2 Transmitter

The satellite requires one Ku-band transmitter and a number of UHF transmitters. Both UHF and Ku-band transmitters are designed using solid-state power amplifiers (SSPA) that are expected to be developed by 1990. The payload power is 2606 watts and 2860 watts for the east and west satellites, respectively (see section 3.7).

A payload power budget, shown in Table 3-8, indicates that the total transmitter power is 2024 watts and 2290 watts for the east and west satellites. Assuming an overall DC-to-RF conversion efficiency of 26%, the RF output is 22 watts per UHF transmitter for the east satellite, and 28 watts for the west satellite. The Ku-band transmitter is 27 watts and 30 watts for the two satellites. Using a 6-watt SSPA, a linearized output power of 30 watts can be obtained with an overall efficiency of about 26% and an intermodulation isolation of 24 to 26 dB [2]. The weight of this transmitter is approximately 6 lbs and its dimension is 3 X 37 X 13 cm (1 X 14.5 X 5.2 inches).

3.5.3 Diplexers

There are two types of diplexers: UHF and Ku-band diplexers. The Ku-band diplexer is designed to handle over 100 watts of peak power. It has an 80-dB receive/transmit isolation, a 60-dB UHF/Ku isolation, and an insertion loss of 1.0 dB. The UHF diplexer is similar to the Ku-band diplexer and can handle an instantaneous power of 300 watts.

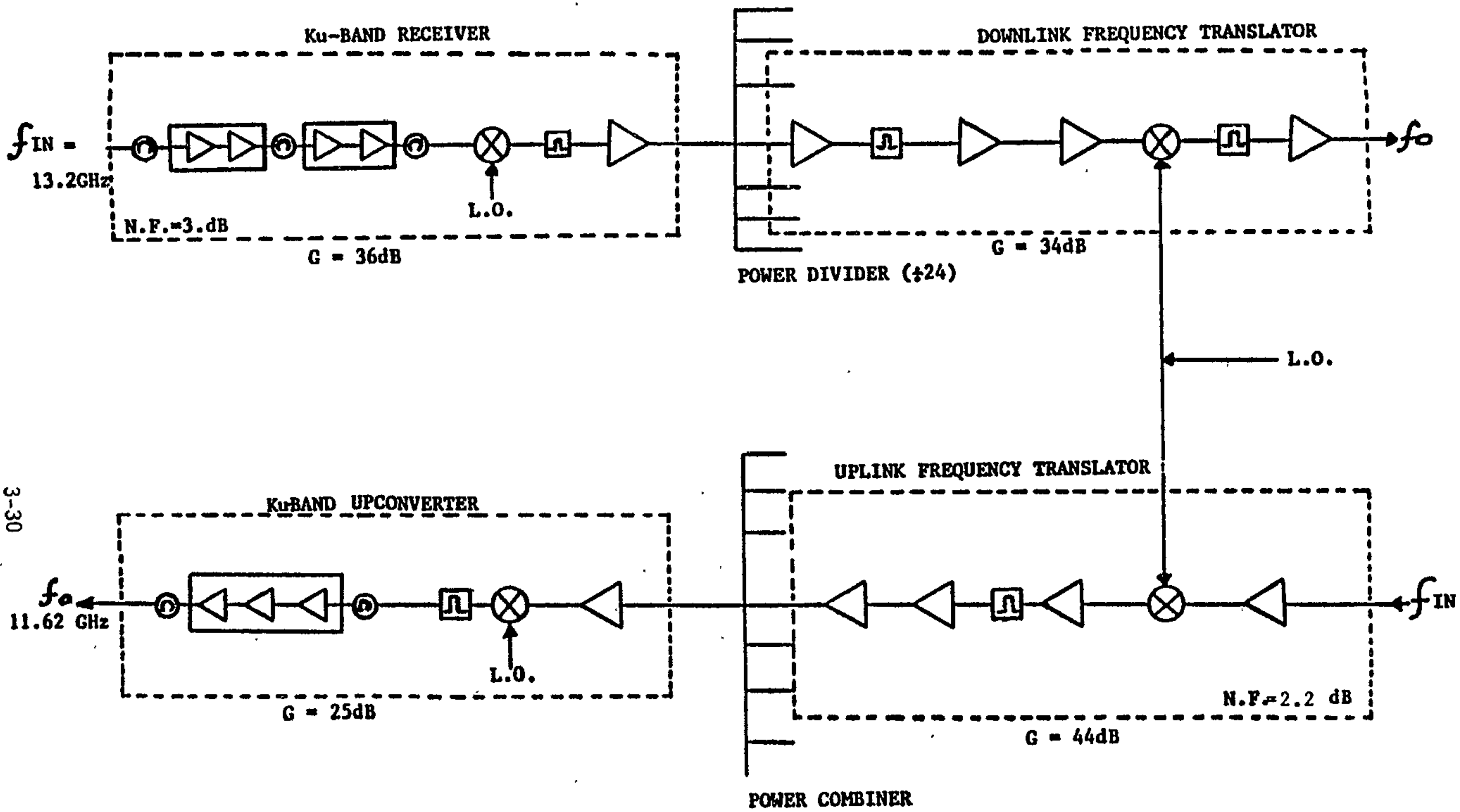


Figure 3-10. A Block Diagram for the UHF and Ku Receiver/Translator [2]

Table 3-7. Receiver Components Technology Chart

COMPONENT	MICROWAVE INTEGRATED CIRCUITS	INTEGRATED CIRCUITS	HYBRID CIRCUITS
Ku-BAND RECEIVER	X	X	X
DOWNLINK FREQUENCY TRANSLATOR			X
UPLINK FREQUENCY TRANSLATOR		X	X
Ku-BAND UNCONVERTER	X		X
LOCAL OSCILLATOR	X	X	X

Table 3-8.

Communication Payload Power Budget

	East Satellite (watts)	West Satellite (watts)
UHF HPA	2024	2290
Ku-Band HPA	102	115
Receiver/Translator	300	264
Upconverter/Downconverter	30	30
Margin	150	161
Total Payload DC Power	2606	2860
Total RF Power (UHF)	526	595
RF Power Per UHF Transmitter	22	28
Total RF Power (Ku)	27	30
RF Power Per Ku Transmitter	27	30

3.6 ANTENNA/FEED DESIGN

In Sections 2.5 through 2.7 design trade-offs for a multi-beam reflector antenna in terms of geometric characteristics, power requirements, frequency reuse schemes, and C/I were given. A variety of examples were also presented. Here the selected baseline configuration is summarized.

The geometric parameters of the 20-meter antenna operating at the high UHF range of 870 MHz, together with the feed characteristics are given in Figure 3-11. The selected feed is a simple 1-element (composed of 4 patches) configuration which seems to satisfy the requirements of power and weight as well as the C/I of the systems. Beam layouts of this antenna at 90° and 130° west longitude have already been given in Section 2.6 (Figures 2-38 through 2-40). The same multibeam layouts, but in a rectangular longitude-latitude system, are given in Figures 3-12 and 3-13. The corresponding feed array layouts are given in Figures 3-14 and 3-15. A universal feed array which may be used in either position as well as on a spare satellite is given in Figure 3-16. Table 3-9 presents a summary of the size and weight of the feed array.

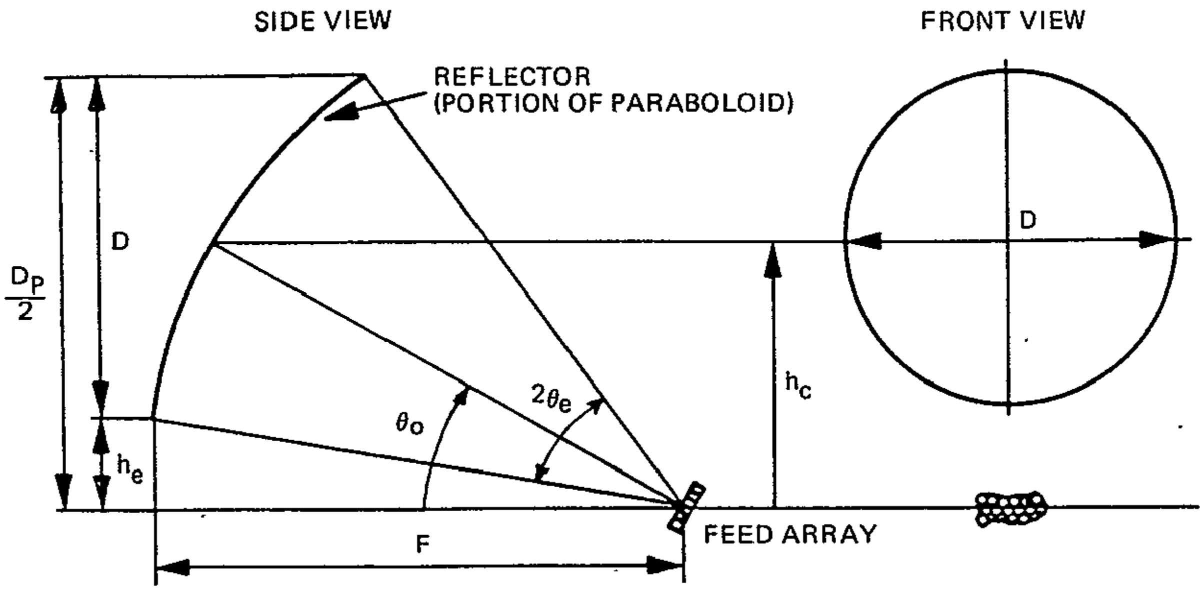
Far-field patterns of the focal point beam are given in Fig. 3-17. A difference of approximately 0.6 dB at the center gain between uplink (823 MHz) and downlink (868 MHz) is computed. However, due to the fact that the lower frequency beams are slightly wider than the higher frequency ones, the amount of gain difference at the 4-dB edge of the beam would be less than 0.1 dB. Figure 3-18 shows a scanned pattern at the edge of the coverage region (beam number 6 in Figures 2-38 through 2-40 and 3-12) whose scan loss is less than 0.5 dB. Table 3-10 summarizes the gain loss mechanisms and the final gain figures. From a study of the beam arrangement in the 24-beam system of Figures 2-39 and 3-12,

Table 3-9. Feed Array Weight for the 20-m UHF Reflector of the Baseline MSAT-2 Design

	Area 24(21) Beams	Weight 24(21) Beams
Radiating elements layer	5(4.5)m^2	10(9) kg
Feed distribution network layer		10(9) kg
Backup structure		30(27) kg
Cables		20(18) kg
Total		70(63) kg

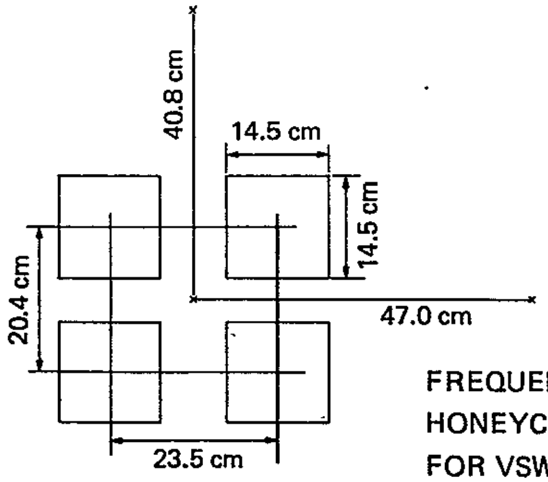
Table 3-10. Gain Loss Breakdown for MSAT-2 UHF Antenna

Aperture Gain, $(\pi D/\lambda)^2$ Center Frequency (845.5 MHz)	45.0 dB
Aperture and Spillover Loss	1.6 dB
Surface Tolerance Loss, for RMS Surface Roughness: 1/60 of Wavelength	< 0.3 dB
Feed Insertion Loss	< 0.2 dB
Feed Conductor and Dielectric Loss	< 0.10 dB
Cross-Polarization Loss	< 0.10 dB
Reflector Surface Reflectivity Loss	< 0.1 dB
4-way Divider Network Loss	< 0.3 dB
Total Gain Loss for Focal Beam	2.7 dB
Focal Beam Gain	42.3 dB
Gain Loss for Maximum Scan 4 Beamwidth	0.4 dB
Uplink (823 MHz) Peak Gain Increment Edge Gain Increment	- 0.3 dB + 0.25 dB
Downlink (868 MHz) Peak Gain Increment Edge Gain Increment	+ 0.3 dB - 0.25 dB



$D = 20m$
$F = 20m, F/D = 1.0$
$h_e = 2m$
$h_c = 12$ cm
$D_p = 44.0m, F/D = 0.45$
$\theta_o = 33.4^o$
$2\theta_o = 51.9^o$

(a) REFLECTOR



FREQUENCY: 845.5 MHz, WAVELENGTH: 35.5
HONEYCOMB SUBSTRATE – THICKNESS: 1.8 cm
FOR VSWR = 1.5 – DIELECTRIC CONSTANT: 1.17
POLARIZATION: CIRCULAR

(b) FEED ELEMENT COMPOSED OF MICROSTRIP PATCHES

Figure 3-11. Feed/Reflector Parameters for the 20m UHF Antenna of MSAT-2

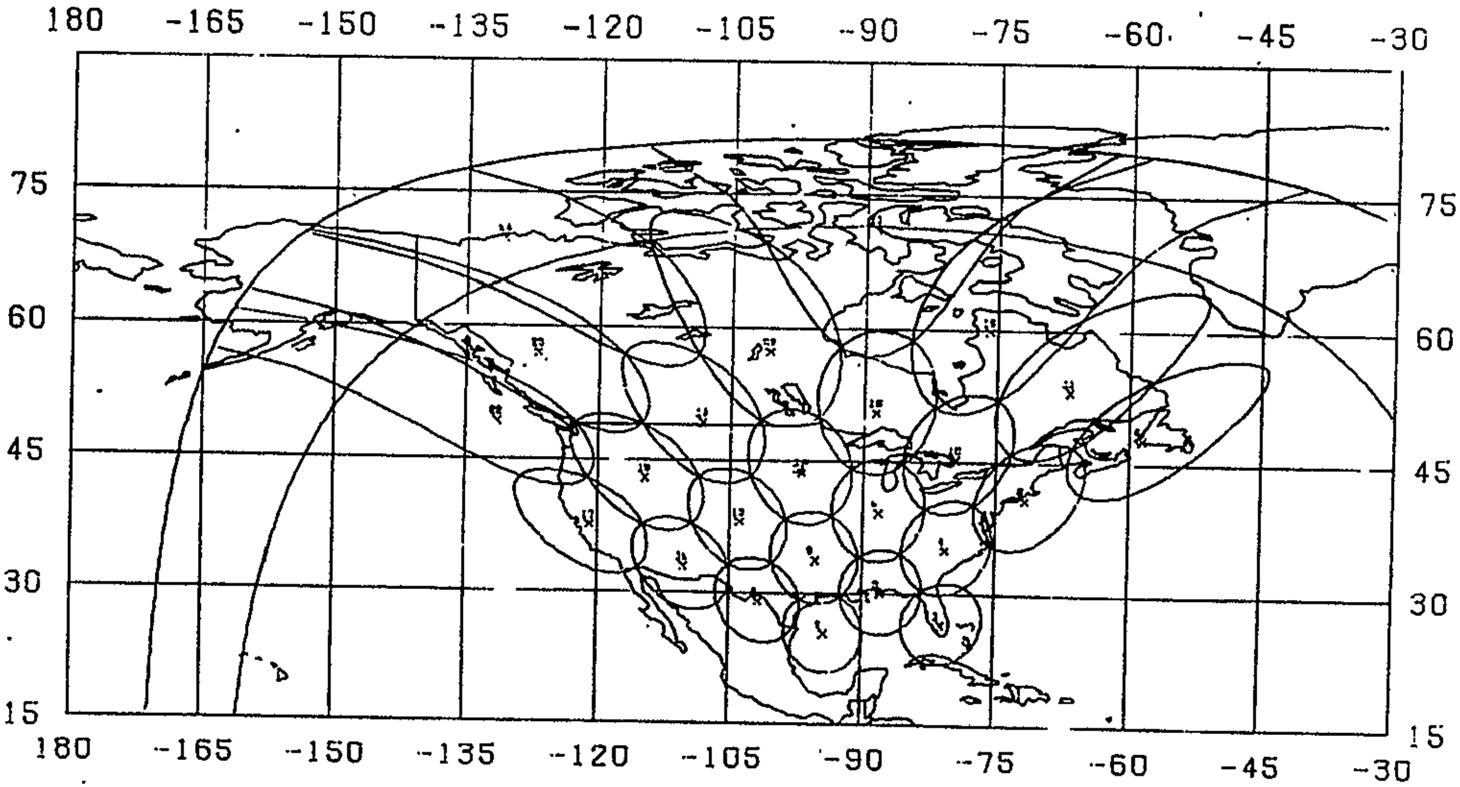


Figure 3-12 MSAT-2 Satellite Antenna Beam Layout in Longitude-Latitude Map
Antenna Diameter: 20 Meter; f: 845.5 MHz; Crossover Beamwidth: 1.4°;
Crossover Gain: 37.9; Satellite Position: 90° W. Longitude Geostationary Orbit

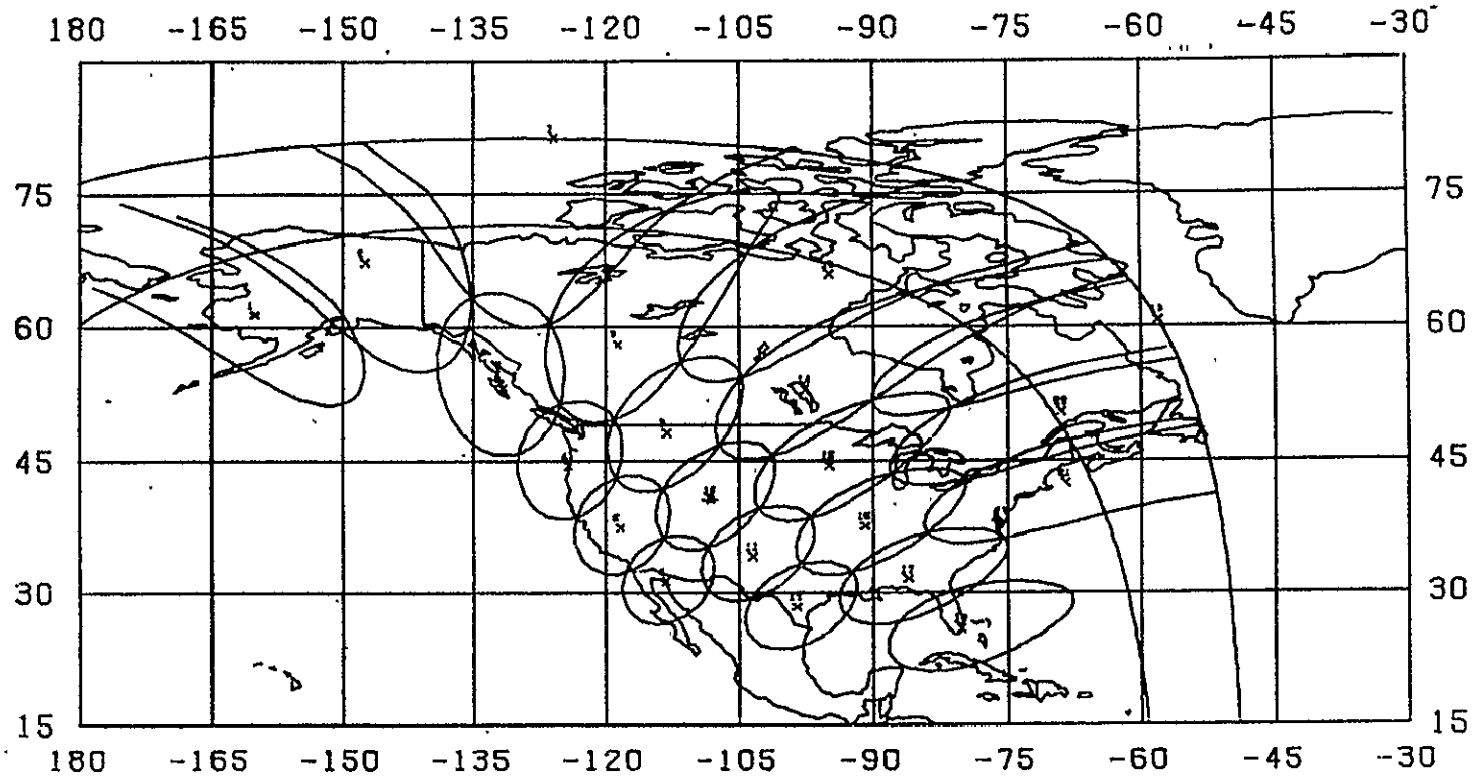


Figure 3-13 MSAT-2 Satellite Antenna Beam Layout in Longitude-Latitude Map
Antenna Diameter: 20 Meter; f: 845.5 MHz; Crossover Beamwidth: 1.4°;
Crossover Gain: 37.9; Satellite Position: 130° W. Longitude Geostationary Orbit

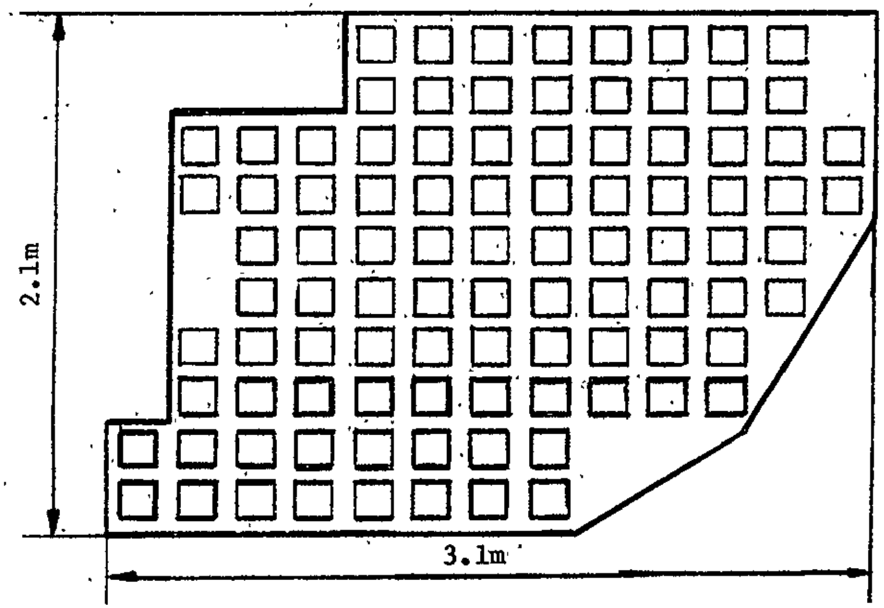


Figure 3-14: Feed Array Configuration for MSAT-2 20m Reflector Antenna: 90° W. Longitude, 24 Beam Coverage

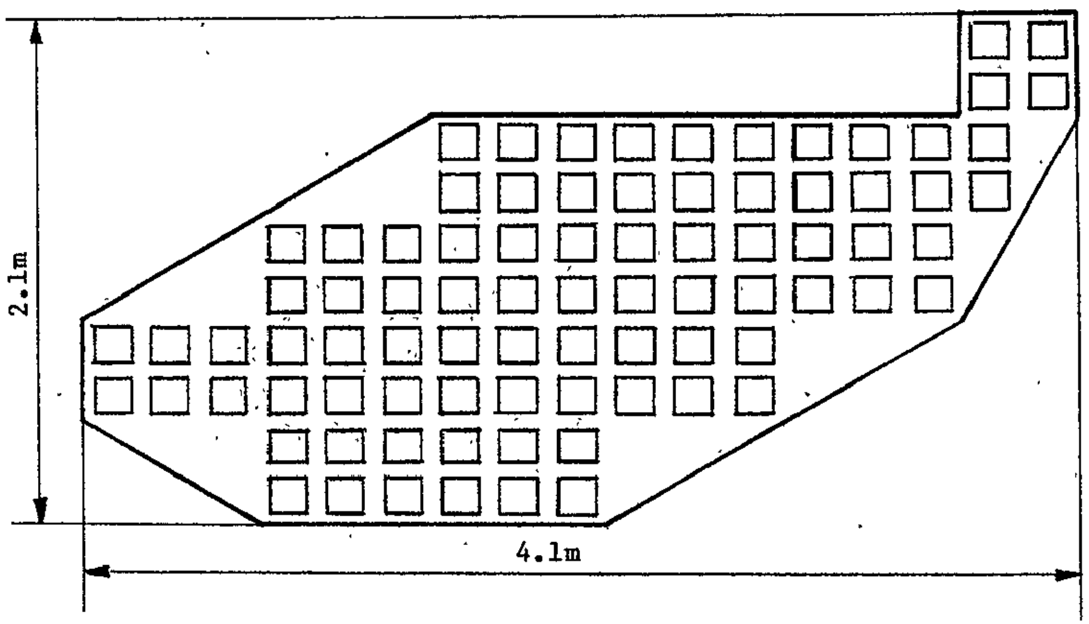


Figure 3-15. Feed Array Configuration for MSAT-2 20m Reflector Antenna: 130° W. Longitude, 21 Beam Coverage

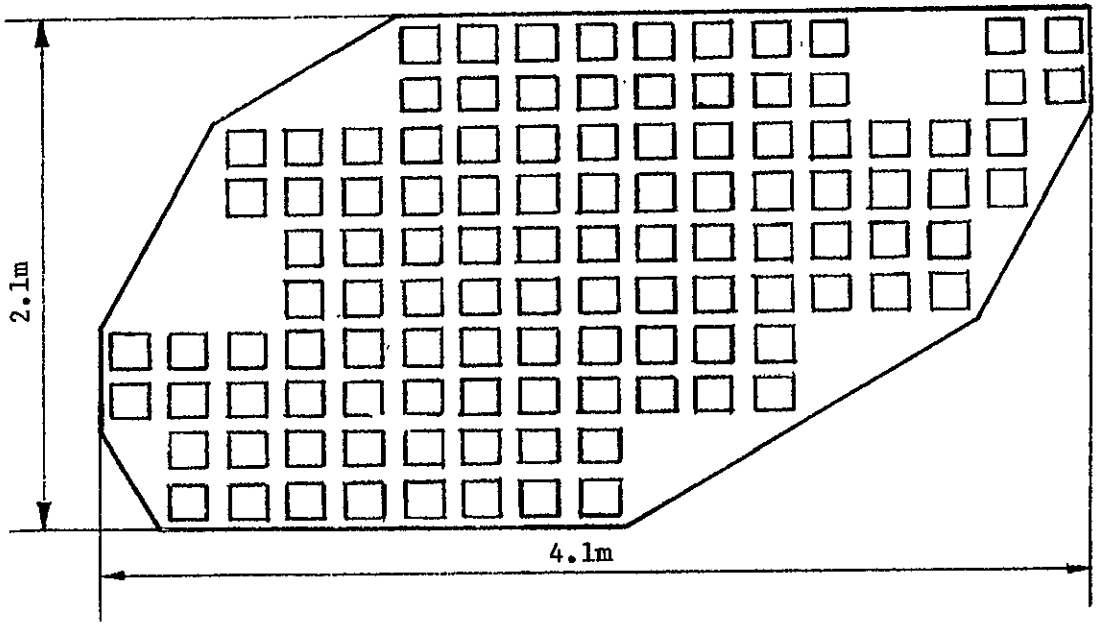
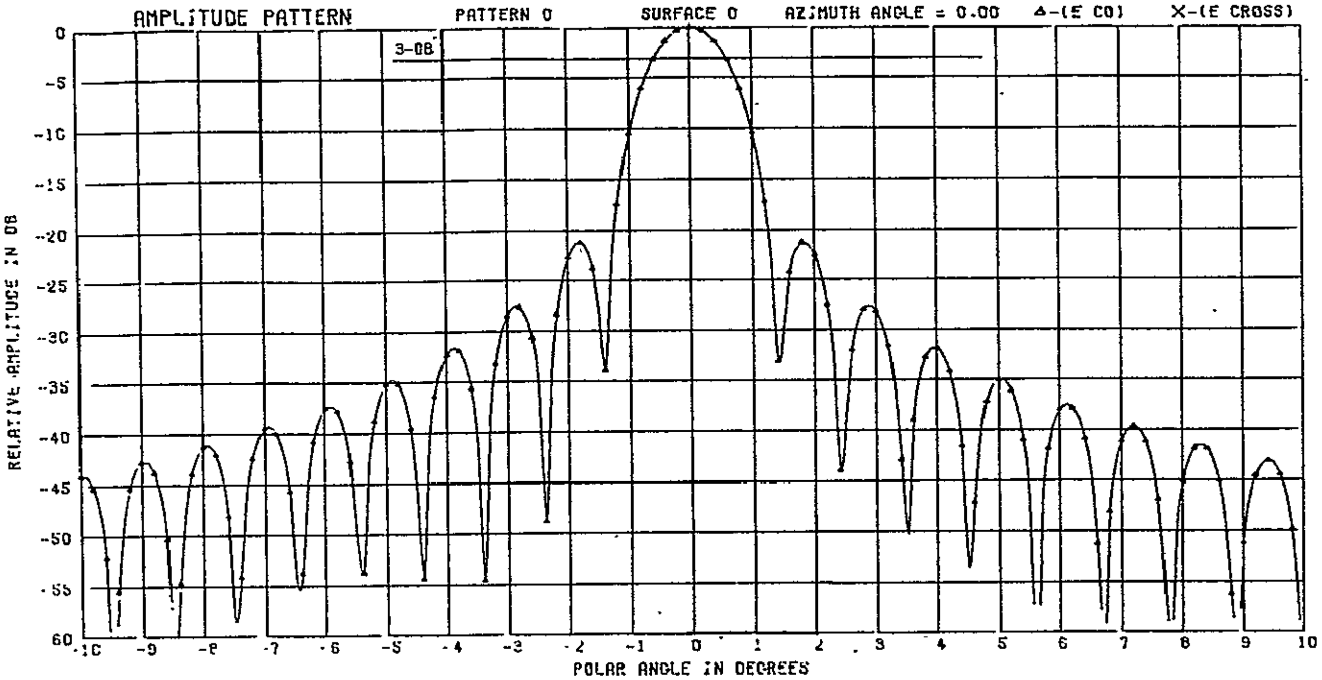


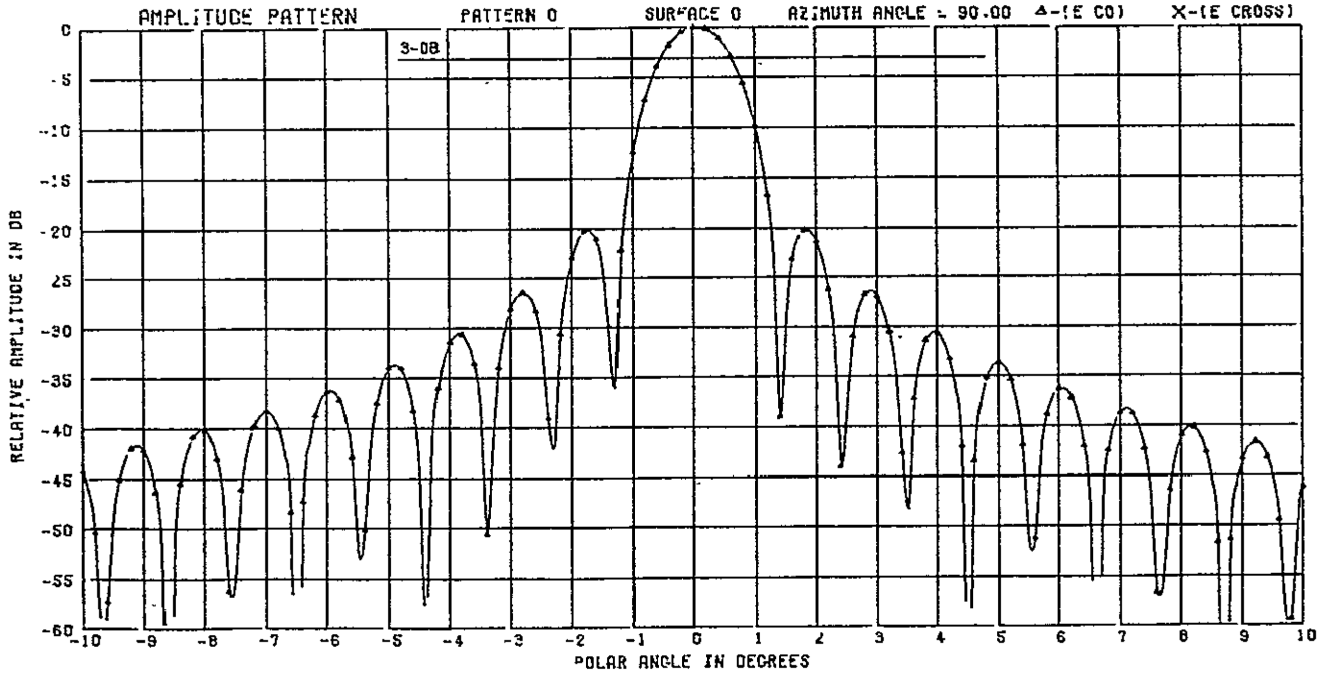
Figure 3-16. Universal Feed Array Panel Configuration for the 20m Reflector Antenna of MSAT-2, for use at Both 90° and 130° W. Longitude Geostationary Orbit

D=54.9.F=54.9.HC=32.94.OMEG=146.6. QX=0.QY=0
BEAM DIRECTION:THETR= .00 PHIR= .00 GAIN= 43.08 EFFICIENCY= 68.37%
PATTERN AXIS:THETB= .00 PHIB= .00 PATTERN PLANE: PHI= .00
LEFT CIRCULAR POLARIZATION



(a) PATTERN CUT IN THE OFFSET PLANE

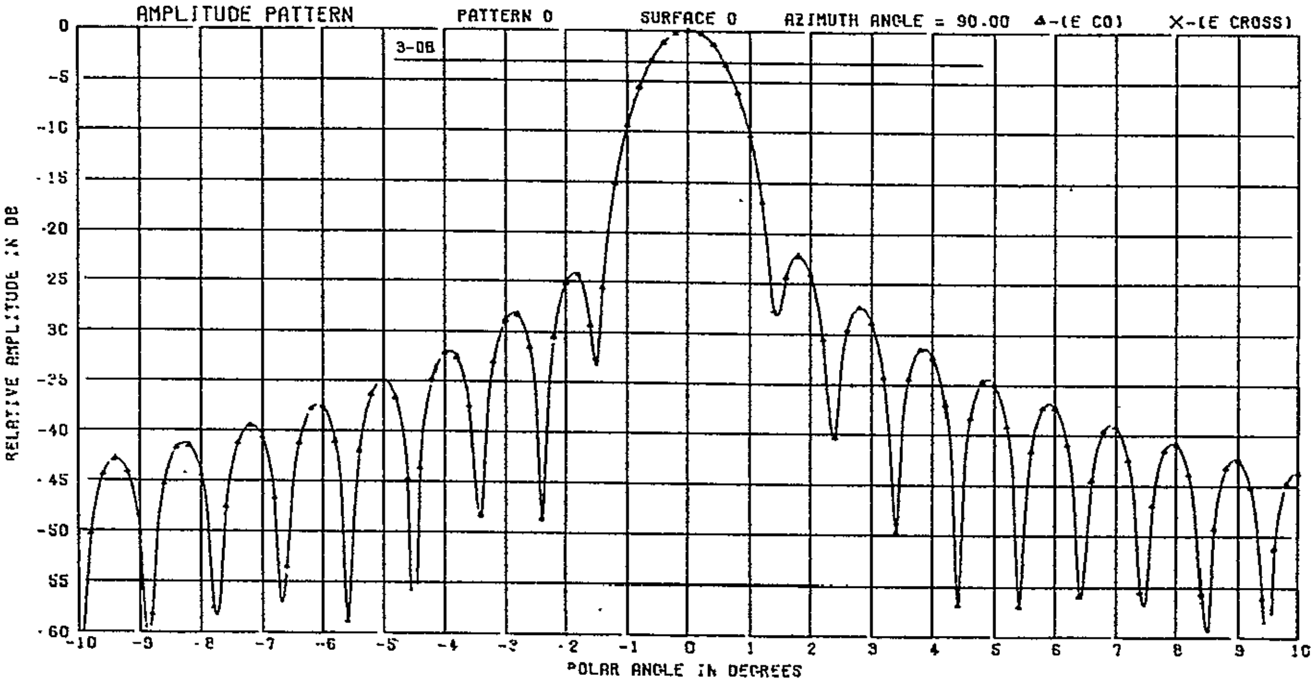
D=54.9.F=54.9.HC=32.94.OMEG=146.6. QX=0.QY=0
BEAM DIRECTION:THETR= .00 PHIR= .00 GAIN= 43.08 EFFICIENCY= 68.37%
PATTERN AXIS:THETB= .00 PHIB= .00 PATTERN PLANE: PHI= 90.00
LEFT CIRCULAR POLARIZATION



(b) PATTERN CUT NORMAL TO THE OFFSET PLANE

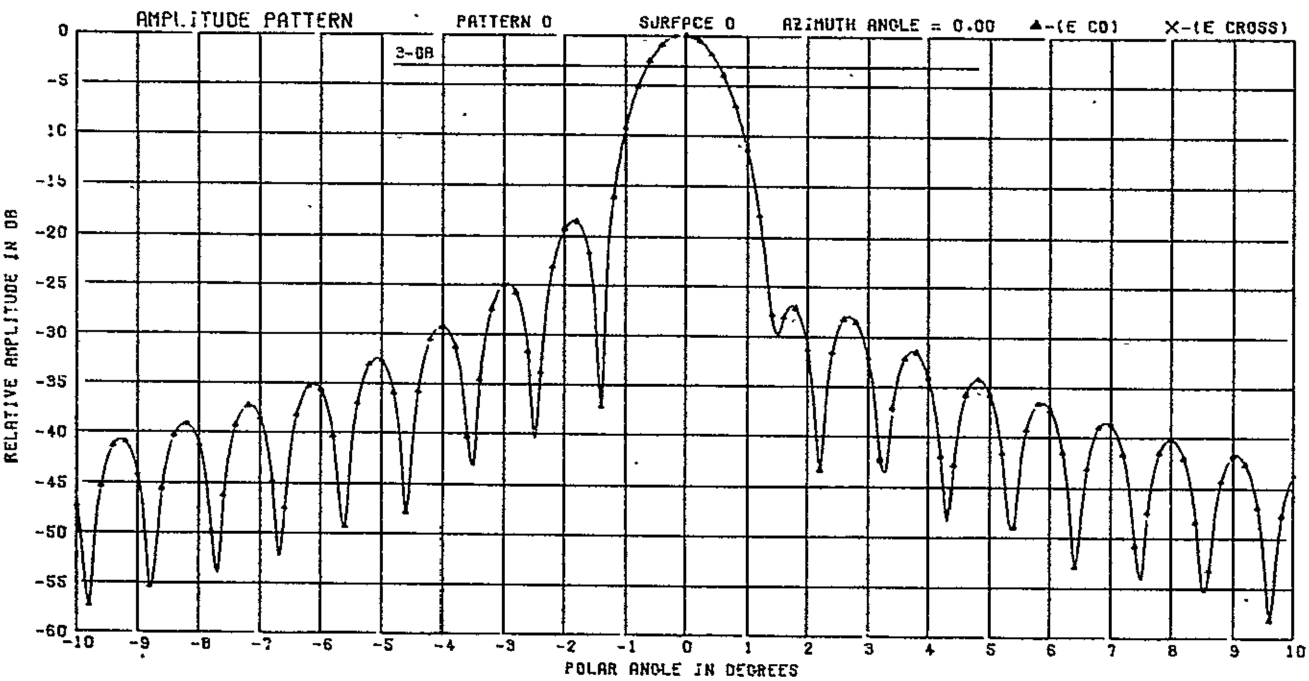
Figure 3-17. On-Focus Pattern of 20-Meter Offset Reflector

D=54.9.F=54.9.HC=32.94.OMEG=146.6. QX=0.QY=3.96
BEAM DIRECTION:THETR= 3.79 PHIR= 90.00 GAIN= 42.63 EFFICIENCY= 61.59%
PATTERN AXIS:THETB= 3.79 PHIB= 90.00 PATTERN PLANE: PHI= 90.00
LEFT CIRCULAR POLARIZATION



(a) PATTERN CUT IN THE OFFSET PLANE

D=54.9.F=54.9.HC=32.94.OMEG=146.6. QX=0.QY=3.96
BEAM DIRECTION:THETR= 3.79 PHIR= 90.00 GAIN= 42.63 EFFICIENCY= 61.59%.
PATTERN AXIS:THETB= 3.79 PHIB= 90.00 PATTERN PLANE: PHI= .00
LEFT CIRCULAR POLARIZATION



(b) PATTERN CUT NORMAL TO THE OFFSET PLANE

Figure 3-18. Pattern of a Scanned Beam (by Three Beamwidths in a Direction Normal to Offset Plane) for 20-Meter Offset Reflector

the achievable C/I's have been approximately calculated and summarized in Table 2-6. For the baseline design the 7-frequency reuse has been selected. For this configuration, accurate contour plots of C/I values over several beam footprints were produced. Beam number 8 in Figures 2-39 and 3-12 seems to be affected the worst by interference. The interference comes from cochannel beams 5, 17, and 21. A contour plot of the isolation levels is produced in Figure 3-19. This figure shows a better than 21-dB isolation for over 90% of the actual hexagonal coverage area. This plot is based on the vectorial summation of the theoretically computed far-field patterns of the beams involved. It does not include the effect of surface tolerance on the pattern. We estimate that for a surface tolerance of no worse than 1/50 of the wavelength, the actual C/I is reduced by about 1 dB.

3.7 POWER SUBSYSTEM

If the satellite were designed to have full north-south station-keeping and 100% eclipse capability, the estimated payload power would be approximately 1360 and 1660 watts for the east and west satellites, respectively, as indicated in Table 2-9 and Figure 2-7. More power will be available to the communications subsystem because the baseline design assumes a reduced eclipse capacity and reduced north-south station-keeping. Reducing the eclipse capability from 100% to 50% results in an additional 400 to 500 watts. Relaxing the north-south station-keeping to ± 2 degrees can bring an additional 846 and 800 watts for the east and west satellites respectively, giving a total payload power of 2606 watts for the east satellite, and 2860 watts for the west satellite (see Table 3-11). To meet the power requirement, the solar array must be sized to provide about 3200 watts of DC power at the end of 10

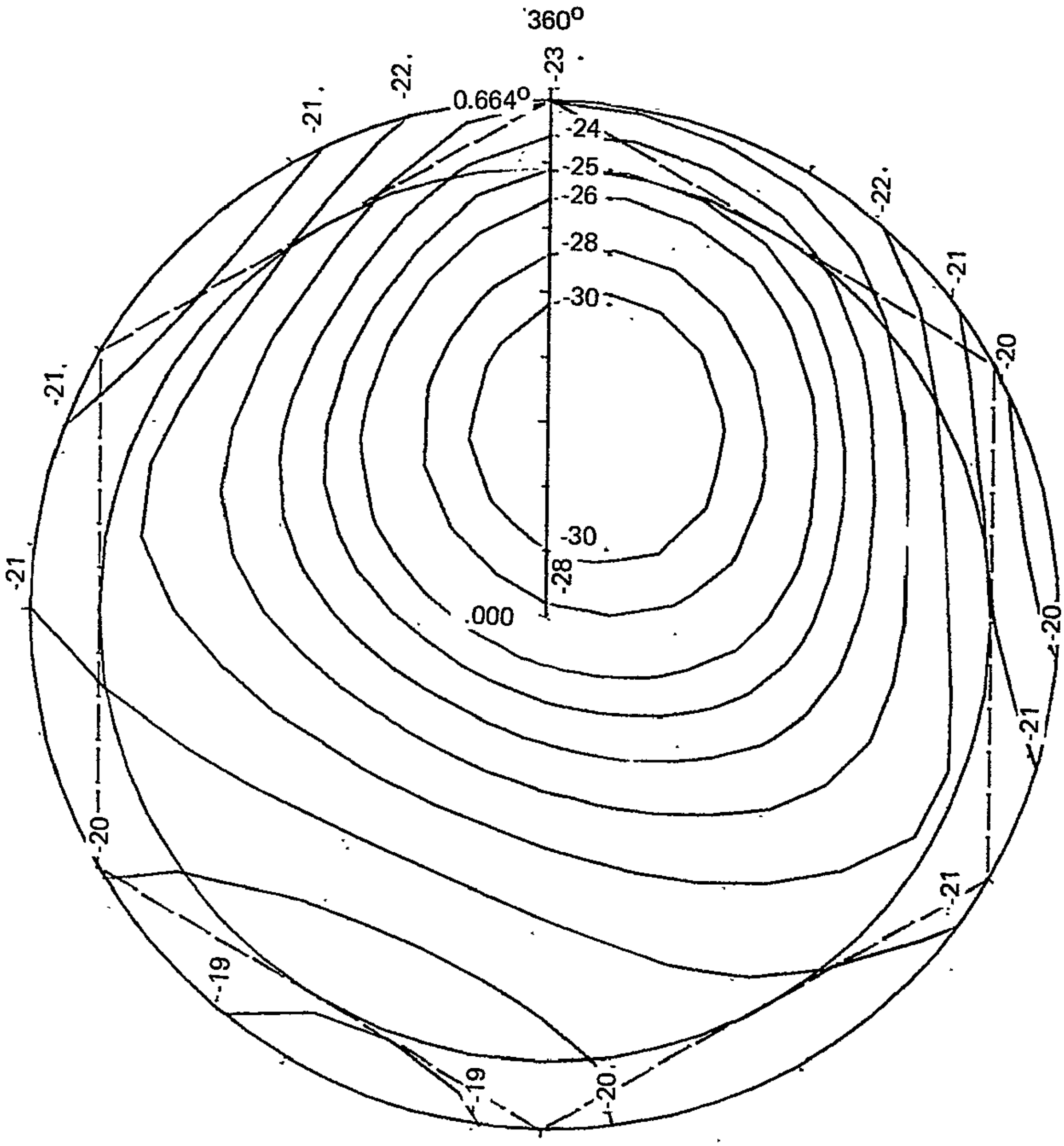


Figure 3-19. MSAT-2 Isolation Contour for Beam 8, of the 7-Frequency Reuse 20-meter UHF Antenna

Table 3-11.

Available Payload Power

	East Satellite	West Satellite
Payload Weight, kg	490	458
Available Power, watts	1360	1660
Additional Power, watts		
Reduced Eclipse Capability	400	400
2° North-South Station-Keeping	846	800
Total Payload Power, watts	2606	2860

years at summer solstice. A power budget for the east and west satellites is shown in Table 3-12. To generate the needed power, the array consists of two identical wings. Each wing has four solar panels, and is about 2.1 m (6.9 ft) by 11.1 m (36.4 ft). The power-to-area ratio of the array is about 90 watts/m^2, and the power-to-mass ratio is roughly 32 watts/kg.

3.8 ATTITUDE CONTROL SUBSYSTEM

One of the challenges posed by the baseline design is the ability of the attitude control subsystem to handle the large reflector and its supporting structure. Based on information obtained from satellite manufacturers, the existing attitude control subsystem is believed to be adequate without major modifications. The pointing accuracy of the antenna is 0.15 degree or better.

3.9 THERMAL SUBSYSTEM

The thermal subsystem must be capable of dissipating the heat generated by the commmunication payload and the satellite bus. The communication payload power is 2.6 to 2.9 kW (see Table 3-11). The amount available to the transmitter is only 2 to 2.3 kW (Table 3-8.). Assuming an overall DC-to-RF conversion efficiency of 26%, the amount of heat generated by the communication payload is about 1.7 kW. The heat generated by the satellite bus is about 400 watts. The total heat dissipation required is thus 2.1 kW, which is well within the capability of the thermal subsystem of the high-power communications satellites. For example, the Advanced Communications Satellite Bus being developed by FACC is designed to be capable of dissipating 2100 watts of heat from the communications module and 500 watts from the bus. No modifications of the existing design of the thermal subsystem are anticipated for MSAT-2.

Table 3-12.

Satellite Power Budget (EOL, Summer Solstice)

	East Satellite	West Satellite
Communication Payload, watts	2606	2860
TT & C, watts	17	17
Housekeeping, watts	292	292
Battery Charging, watts	45	45
Total, watts	2960	3214

3.10 MASS SUMMARY

The weights of various subsystems have been estimated using information obtained from satellite manufacturers, data contained in [1], [2], [6], and [7], and the payload weight model in Appendix D. The estimated spacecraft weight is 1573 kg (3460 lbs) at BOL, 2840 kg (6248 lbs) at GTO, and 8600 kg (18,920 lbs) in the STS cargo bay. The weight summary is shown in Table 3-13.

The launch cost associated with the mass of the cargo corresponds to a charge factor of 0.38.

3.11 FREQUENCY PLAN

The baseline system is designed to provide mobile service using the UHF and Ku-band frequencies. The assumed UHF allocation is a pair of 10-MHz bands, each contains a 4-MHz and a 6-MHz segment (see Figure 1-10). To efficiently utilize the available frequency band, a 7-frequency reuse scheme is employed, where both the uplink portion and the downlink portion of the band are divided equally into 7 frequency subbands, each of 1.428 MHz wide. Each frequency subband is further divided into 285 channels of 5 kHz each. Figure 3-20 shows the uplink frequency plan. The downlink frequency plan is identical.

The assumed allocation for the backhaul link is a 50-MHz band pair in the Ku-band, with 50 MHz for uplink and 50 MHz for downlink. The 50-MHz band is divided into 24 segments of 1.4 MHz each. A guard band of 0.7 MHz between adjacent segments will reduce potential interference between adjacent segments.

The UHF-to-Ku and Ku-to-UHF translations are accomplished by uniquely associating a Ku-band segment to a particular UHF beam. An example is shown in Figure 3-21 for the east satellite. In this example, all uplink signals received

Table 3-13. Mass Summary

	East Satellite kg	(West)
Communication Payload	490	(458)
TT & C	24	
ACS	70	
Propulsion	141	
Power	221	
Structure	156	
Thermal	36	
Electrical Integration	51	
Mechanical Integration	15	
Margin	135	(167)
Dry weight	1339	(1339)
Station-Keeping Fuel	234	
BOL Weight	1573	(1573)
Apogee Propellant	1269	
GTO Mass	2842	(2842)
Cargo Mass	8600	(8600)

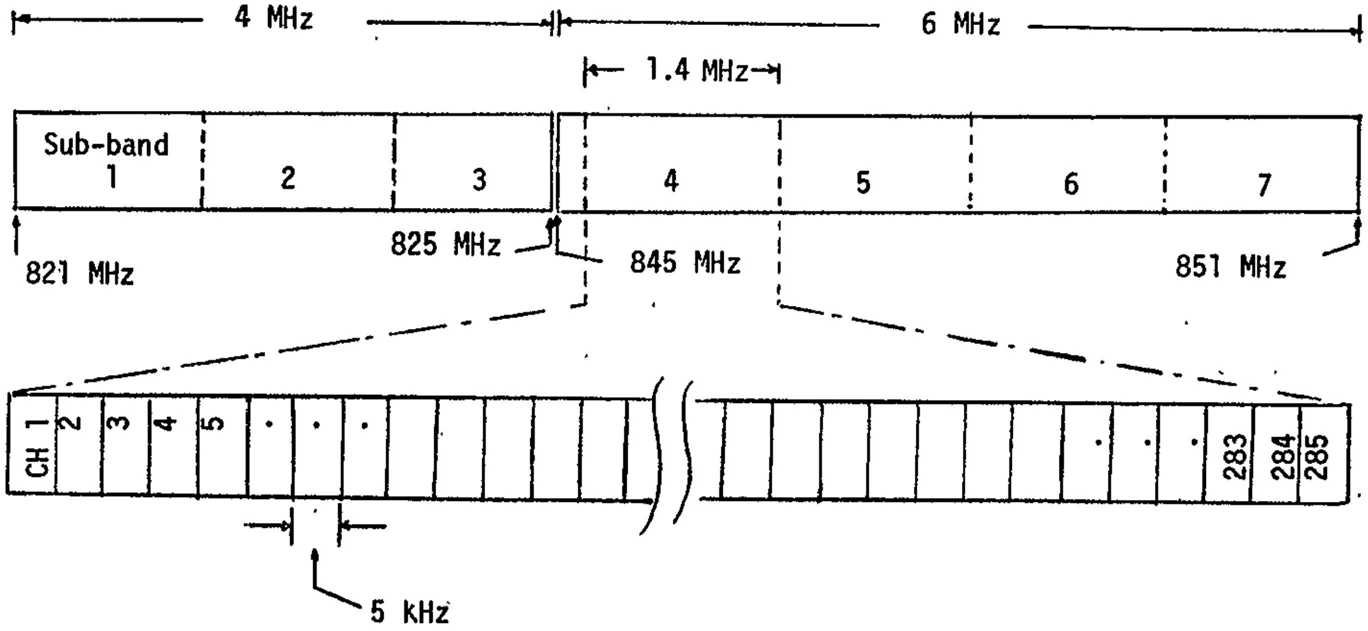


Figure 3-20. UHF Uplink Frequency Plan

(The downlink plan is the same)

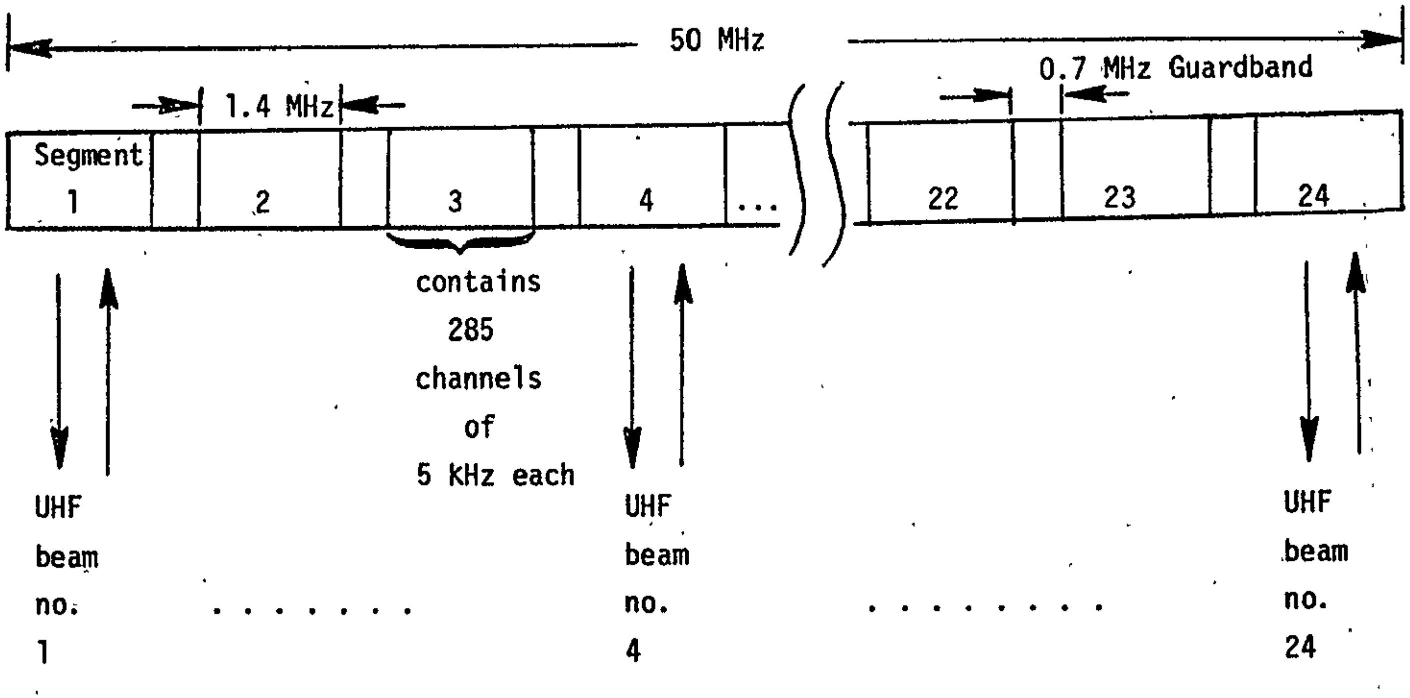


Figure 3-21. Ku-Band Frequency Plan and Ku/UHF Translation (An Example)

from beam No. 1 will be translated to segment 1 for retransmission. Similarly, all uplink Ku-band signals that are in segment 1 will be transponded back via UHF beam No. 1.

The west satellite employs 21 beams to provide the required coverage. The Ku-band requirement is slightly less than 50 MHz.

3.12 SYSTEM CAPACITY

The available RF power is 526 watts for the east satellite, which can power up about 4076 channels at 0.13 watts/channel. The available RF power for the west satellite is 595 watts and the resulting number of satellite channels is 4612. The total system capacity is thus 8688 channels. However, due to a skewed user distribution, the effective capacity is expected to be much less than the actual satellite channels. Allowing a 50% reduction, the system capacity is reduced to 4344 channels.

The number of users that can be accommodated by the system varies over a wide range, depending on the voice-to-data user ratio. Voice service is expected to account for a significant portion of the total service in the beginning, but data users are expected to increase rapidly and eventually may account for a major portion of the user population. Assuming a voice-to-data user ratio of 0.2, the system has a capacity of providing service to about 860,000 users. If the ratio decreases to 0.1, the number of users increases to 1.5 million.

3.13 ESTIMATED USER COST

The mobile satellite system is, as previously mentioned, a commercial system. The amount of investment required is tremendous. Whether MSAT-2 will materialize depends, to a large extent, on the financial viability of the

system. One way to measure the financial health of the system is to estimate the user cost using the cost model in Appendix C.

As will be pointed out in Chapter 6, the user cost is composed of the system cost, mobile equipment cost, and the cost of using a terrestrial wireline network. The system cost and the mobile equipment cost will be examined in the following sections. The cost associated with the usage of the wireline network will not be considered.

3.13.1 System Cost

The system cost includes the satellites, launch service, ground equipment, insurance, profits, operation, and maintenance (please see Chapter 6). The cost of three satellites is estimated to be $276 M, in 1985 dollars. The cost of the perigee stage, capable of delivering the MSAT-2 payload, is included in the cost of the satellites. Also included is the manufacturer incentive. Launch services for three satellites cost $165 M, based on a stowed length of 7.3 m (24 ft) corresponding to a charge factor of 0.533. Launch insurance costs $60 M. The cost of the NMC, which includes the Distributed Command Centers (DCC's) and the Network Control Center (NCC), is estimated to be $30 M. (Please see Chapter 4 for more on network elements.) The cost of a TT&C station having a limited motion tracker is about $7 M. Assuming two TT&C stations, the cost will be $14 M.

The cost of a gateway station/base station varies over a wide range, depending on the size of the station, i.e., the number of channels. A station with 50 to 100 channels is estimated to cost $500,000, while one with 200 to 300 channels costs $1 M to $1.5 M. Large stations have the advantage of minimizing the total system cost, but small ones require less initial capital investment,

and hence are more attractive to independent operators. Because the small stations are relatively inexpensive, it is possible to have a large number of such stations spread across the service area. This will, on the average, shorten the distance of the wireline portion of the communications path, and hence reduce the associated wireline charge for those services involving a wireline network. This is an additional advantage of the small stations. While the actual sizes of the stations for MSAT-2 are expected to vary to a certain degree, the total cost of the gateway/base stations is assumed to be $35 M, which is equivalent to the cost of 70 stations having a capacity of 50 to 100 channels each.

The investment return, and the costs of maintenance and operation are discussed in Section 3.13.3.

The cost of the mobile terminal using a mechanical, steerable MGA is estimated to be $2300. It is noted that the mobile terminal cost is not considered as part of the system cost.

The cost estimates are summarized in Table 3-14.

3.13.2 Channel Usage

Channel usage plays a very important role in determining the end user cost. Because of the diurnal variation, the system capacity is not fully utilized all the time. Based on the crude model shown in Figure 2-58, the average usage is only about 45%. Although the model may be somewhat pessimistic, the actual usage factor may not be much higher if one considers other factors, such as the day-of-the week variation and seasonal variation, which have been observed on terrestrial systems. Considering these factors, the usage factor will be assumed to be 50% for MSAT-2. The number of equivalent revenue-

generating channels is thus 2172, or one-quarter of the actual satellite channels.

3.13.3 User Monthly Cost

MSAT-2 is designed to provide both voice and data communications. Because voice communications in general last much longer than data messages, it is necessary to charge the user a fixed service fee, such as a monthly service charge (MSC), in addition to the usage charge based on the amount of usage. This method of charging lowers the charge per call-minute, and allows the cost of the system to be shared more evenly by all users.

Using the data tabulated in Table 3-14, and the cost model in Appendix C, the user cost for the baseline design has been established for various combinations of monthly usage and MSC. The estimated cost is graphically shown in Figure 3-22. Depending on the MSC, the monthly cost ranges from about $52 to $59 for a user having 40 call-minutes per month and $65 to $66 for one with 100 call-minutes.All costs are in 1985 dollars. As indicated in the figure, imposing a MSC will benefit users having more than 115 call-minutes per month at the expense of those infrequent users. The charge rate is $.20 per call-minute without a monthly service charge. The rate reduces to $.11 for a MSC of $10.00.

The above user cost includes the cost of the mobile equipment, which is estimated to be $44.50 per month.

The item-by-item cost breakdown is shown in Table 3-15 for selected MSC's and different amounts of usage.

Table 3-14.

Estimated Costs for the Baseline System

	Cost in Constant 1985 Dollars	Comment
Satellite	276M	3 satellites (2 active, plus 1 hot spare).
Launch	165M	3 launches.
Launch Insurance	60M	
NMC	30M	
TT&C Stations	14M	2 TT&C stations with a limited-motion tracker.
Gateway Stations	35M	
Mobile Terminal	2300	With a mechanical, steerable antenna.

Table 3-15.

User Monthly Cost for a User Population of 863,000

Charge Rate, $/Min	Amount of Usage Min/Mo [1]	Monthly Usage Charge $/Mo	Monthly Service Charge $/Mo	Mobile Equipment Cost $/Mo	Total Monthly Cost $/Mo
0.20	10	2.00	0	44.50	46.50
0.20	50	10.00	0	44.50	54.50
0.20	100	20.00	0	44.50	64.50
0.20	150	30.00	0	44.50	74.50
0.20	200	40.00	0	44.50	84.50
0.11	10	1.10	10	44.50	55.60
0.11	50	5.50	10	44.50	60.00
0.11	100	11.00	10	44.50	65.50
0.11	150	16.50	10	44.50	71.00
0.11	200	22.00	10	44.50	76.50

Note:

(1.) Based on one-way communications.

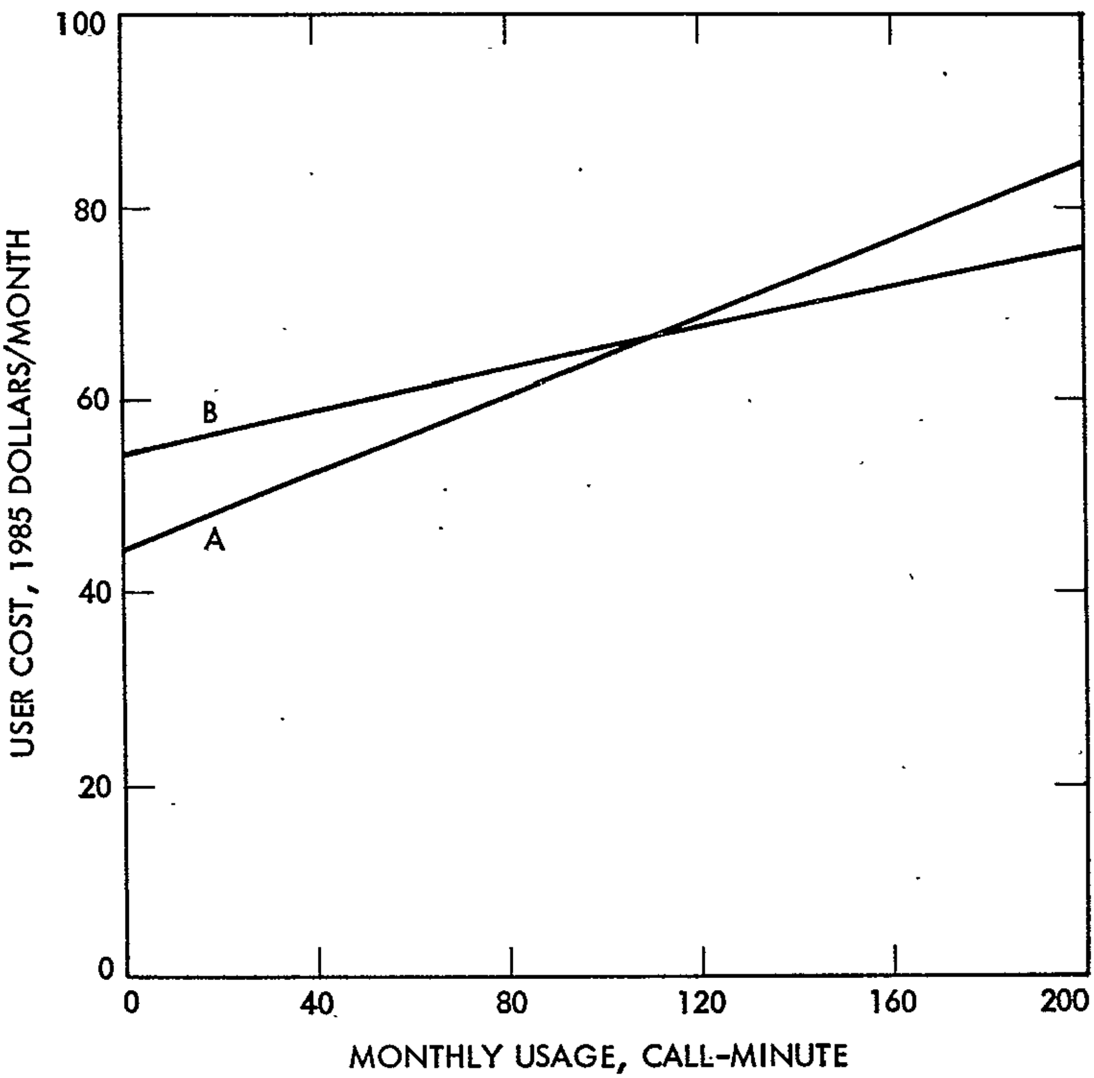


Figure 3-22. User Cost Versus Monthly Usage (One-Way)
A: MSC = $0 B: MSC = $10

As previously mentioned, the calculation of the user cost requires one to estimate the inflation rate, rate of return, operation and maintenance costs, etc. In computing the user cost provided in Table 3-15 and Figure 3-22, the rate of return was assumed to be 20%, which is 12% above the projected inflation rate, the operation cost was $0.05 per call-minute, and the maintenance cost was 1% of the replacement cost of the system.

If the maintenance cost is increased to 10% of the replacement cost and the operation cost to $.10/call-minute, the charge rate would be increased from $.20 to $.33 per minute.

As previously mentioned, the charge per call-minute is based on one-way links where the number of call-minutes is simply the same as the number of channel-minutes. Duplex communications, however, require twice as many channels as the simplex links. One call-minute in a duplex mode is equivalent to two channel-minutes. On a per call-minute basis, the charge for duplex operations should therefore be twice as much as the charge for simplex communications.

REFERENCES

[1] Spacecraft Configuration Study for the Second Generation Mobile Satellite System, Final Report, Ford Aerospace Communications Corporation, January 1985.

[2] Mobile Satellite Configuration Study, Final Oral Report, RCA Astro Electronics, January 23, 1985.

[3] 'MSAT-X System Definition and Functional Requirements,' MSAT-X Document.

[4] 'Mobile Satellite Experiment, Progress Report for October/November, 1984,' MSAT-X Document.

[5] 'Propagation Considerations in Land Mobile Satellite Transmission, Wolfhard J. Vogel and Ernest K. Smith, MSAT-X Report,' No. 105, January 24, 1985.

[6] Land Mobile Satellite Service (LMSS): A Conceptual System Design and Identification of the Critical Technologies, Part II, Technical Report, Firouz Naderi, Ed., JPL Publication 82-19, February 15, 1982.

[7] Final Report for Antenna Technology, LMSC-D971808, Lockheed Missiles and Space Company, Inc., October 12, 1984.

CHAPTER 4

SECOND-GENERATION MOBILE SATELLITE NETWORKING CONCEPT

4.0 INTRODUCTION

The concept of mobile communications through the use of geosychronous satellites has been studied extensively in recent years [1 and 2]. The MSAT-2 is a satellite-based communications network that will provide voice and data communications to mobile users throughout a vast geographical area. The space segment of MSAT-2 consists of two spacecraft in a geosynchronous orbit. The spacecraft transponders act as bent pipes, serving only to translate the frequency of the signals they receive and to retransmit those signals. No switching will be performed by the spacecraft. The ground segment consists of a number of fixed Earth stations, mobile transceivers, a set of distributed command centers, and a network control center. This chapter will describe the networking concept of this second-generation MSAT.

As previously mentioned, communications between the mobile terminals and the satellite are assumed to be in the UHF band. This is referred to as a service link. Communications between the spacecraft and the fixed Earth stations will be provided in the less congested Ku band. This is referred to as a backhaul link. In this chapter an integrated networking scheme for the mobile voice and data communications will be described and analyzed.

4.0.1 Network Elements

The basic network elements are the mobile terminals (MT's), the base stations (BS's), the gateways (GW's), the distributed command centers (DCC's), and a network control center (NCC). The DCC's and NCC together constitute the network management center (NMC) mentioned in previous chapters. Functionally, the MT's and the BS's serve as ultimate connection endpoints. The GW's, on the other hand, provide a relaying function between the MT's and users of another public switched telephone network (PSTN) that is interfaced to the GW. Thus, the PSTN users can communicate with the MSAT-2 mobile-phone users by means of a GW. The DCC's are responsible for the allocation of the satellite resources and for enabling the connections between the network users for a preconfigured group of channels, i.e., intragroup activities are controlled and monitored by the DCC. The last network element mentioned above is the NCC. The NCC will issue commands to the DCC's for all intergroup activities, and keep track of the network accounting and the global network control. Only network control information is passed to and from the NCC. All DCC's are interconnected and closely monitored by the NCC.

There are two types of MT's, namely mobile telephone terminals (MTT's) and mobile dispatch terminals (MDT's). MTT's have only a voice generation/reception capability. BS's and MDT's have both a voice and data generation/reception capability. DCC's and the NCC exclusively use digital signaling for all control communications. Voice reception capabilities may exist for the purpose of monitoring voice channel communication characteristics at DCC's and the NCC.

4.0.2 Network Topologies

Figure 4-1 illustrates the physical topology of the MSAT-2 network. The satellite is assumed to have a multiple UHF beam capability, with a single full-coverage Ku beam. Distinct Ku bands correspond to the UHF band in each beam. Each UHF channel is translated to and from a Ku channel for MT communications with the DCC, a BS, or a GW (see Chapter 3). Communications between the DCC and a BS, the DCC and a GW, or the NCC and DCC's will take place via either a Ku-Ku cross-strap through the satellite, or terrestrial links. All elements of the network must be able to communicate with at least one DCC in a single hop through the satellite. MT-to-MT communications will require two hops through the satellite, with an intermediate BS/GW providing the necessary Ku-Ku translations. Communications between the GW and the switched network it interfaces with would presumably be by terrestrial links. Only network control information will be communicated between DCC's and the NCC.

The logical connectivity of the network is defined as the matrix of all permissible communications paths between network elements. Enforcement of this connectivity is accomplished as part of the channel assignment function in the NCC and DCC's. The general rules that describe the logical connectivity are as follows. Each MT must be associated with a home BS/GW. The connection of an MDT and its associated BS(s), or between an MTT and a user of another PSTN via a GW will be enabled and disabled by a DCC which controls and monitors the intragroup activities. Connections can also occur between any MT's within the coverage of the satellite. Intergroup connections will be handled by the NCC through corresponding DCC's. All MT's, GW's, and BS's can communicate with at least one DCC for the purpose of establishing connections.

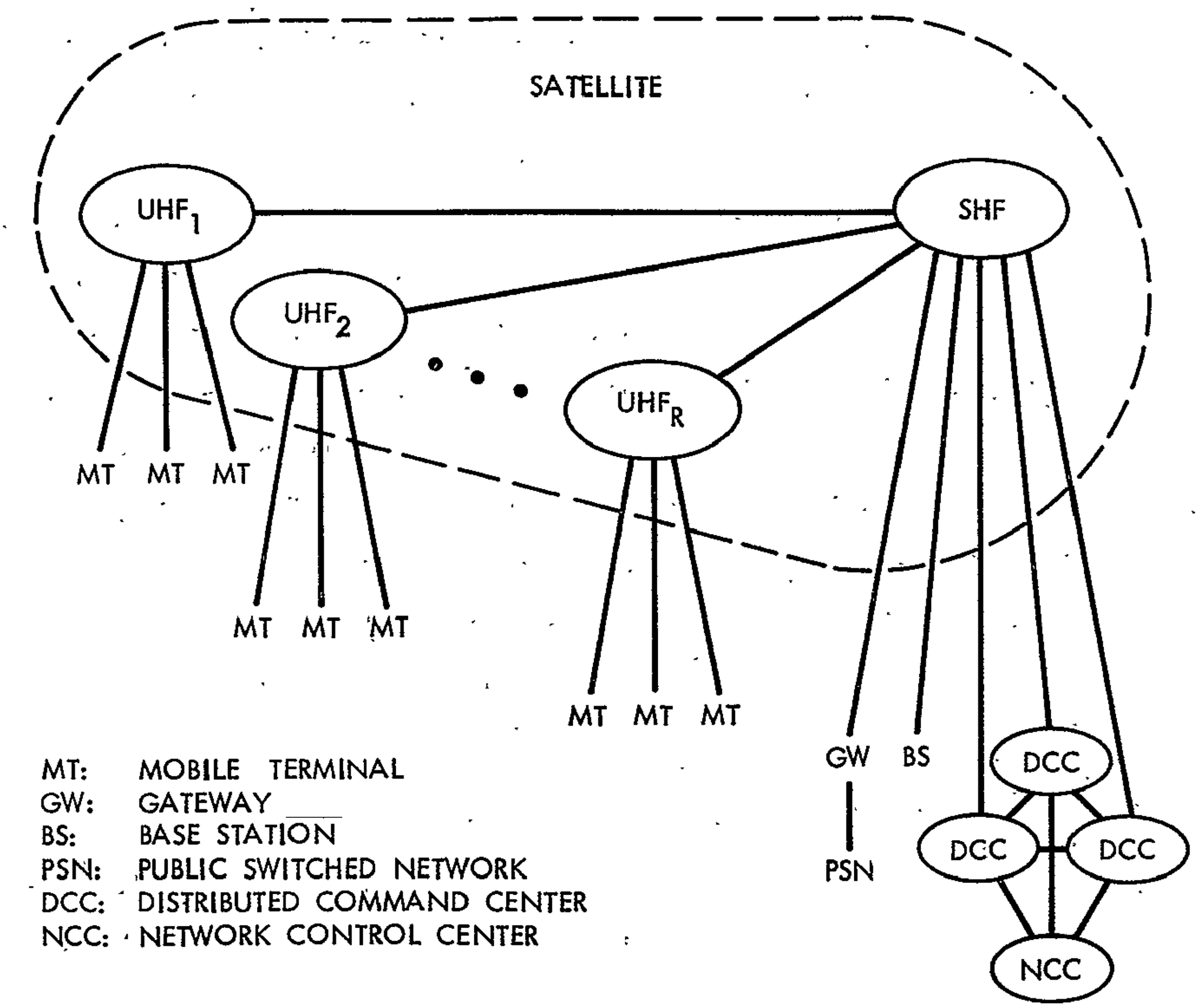


Figure 4-1. General Physical Topology

4.0.3 Network Control

The fundamental resource to be shared among all of the network elements is the satellite and its operational frequency bands. The forward and return link UHF/Ku-frequency bands are divided into 5-kHz channels. (The forward link is from MT to GW/BS/DCC, and the return link is from GW/BS/DCC to MT.) At any given instant, these channels can be dynamically assigned to perform different communications' functions. There are four functional types of channels: reservation channels, command channels, voice channels, and data channels. Reservation channels only occur on forward links, and are used for MT-to-DCC communications for terminal initialization and requests for connection establishments. Command channels only occur on return links, and are used by the DCC to provide control information to the network users, within its group, regarding acknowledgments of reservation channel traffic, connection attempts by other users, and network status information. Voice and data channels occur on both forward and return links and are used for the actual transfer of user traffic in the course of a connection. The distinction between voice and data channels corresponds to the two connection types described in section 4.1.

Efficient utilization of the channels within a group is conceptually accomplished by means of the Integrated-Adaptive Multiple Access Protocol (I-AMAP) algorithm. The channels are partitioned into the functional groups described above. Figure 4-2 illustrates an example partition of the channels; the channels supporting the same function need not be contiguous, but are shown as such for ease of presentation.

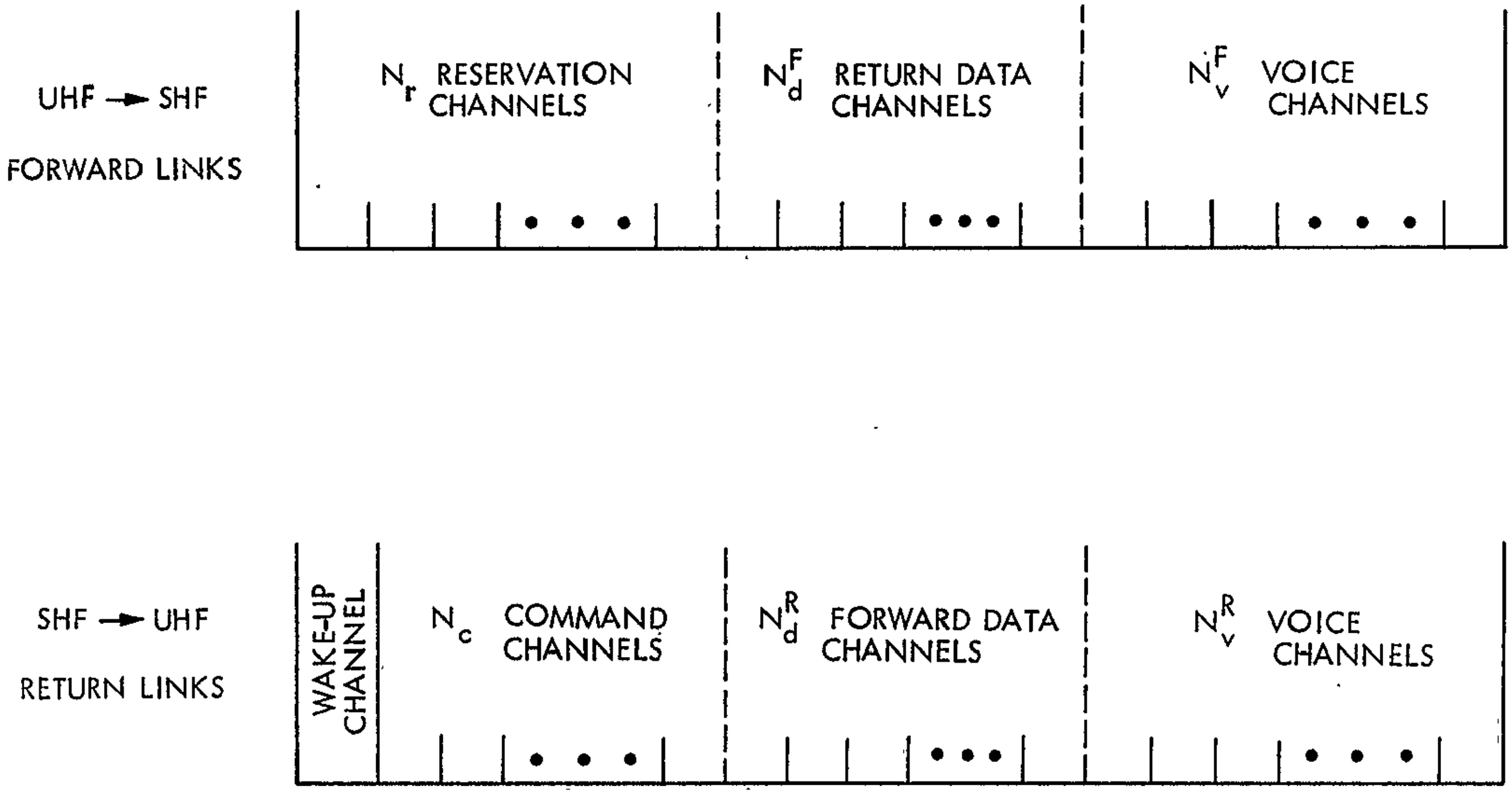


Figure 4-2. Channelization

Figure 4-3 illustrates the intragroup control topology. MT's gain access to the corresponding DCC using the ALOHA protocol over the current reservation channel(s). GW's and BS's make connection requests over the Ku-Ku cross-strapped or terrestrial links with the DCC. The DCC is responsible for processing all requests for communications within its group. The channels are assigned according to the I-AMAP which dynamically allocates the available channels between the voice traffic, the data traffic, and the reservation request traffic on a demand basis. If a channel is available, the DCC notifies the parties of the assignment. Once the assignment has been made, control responsibility is transferred to the intermediate GW or BS. The cognizant GW or BS monitors the call and signals the DCC in the event of errors, such as connection failure or disruption of service. Normal connection termination is initiated by the end users. The GW/BS detects the connection termination request and notifies the DCC so that the channel may be freed for other use.

Figure 4-4 illustrates the intergroup control topology. As in the intragroup connection procedures, MT's first gain access to their corresponding DCC using the ALOHA protocol over the reservation channel(s) within their group. After the DCC detects that the communications request is an intergroup connection, the DCC signals the NCC to establish a connection in the other groups. As soon as the NCC sets up a connection between DCC's, the connection will be maintained by the two associated DCC's. Only control information will be transferred between NCC and DCC's.

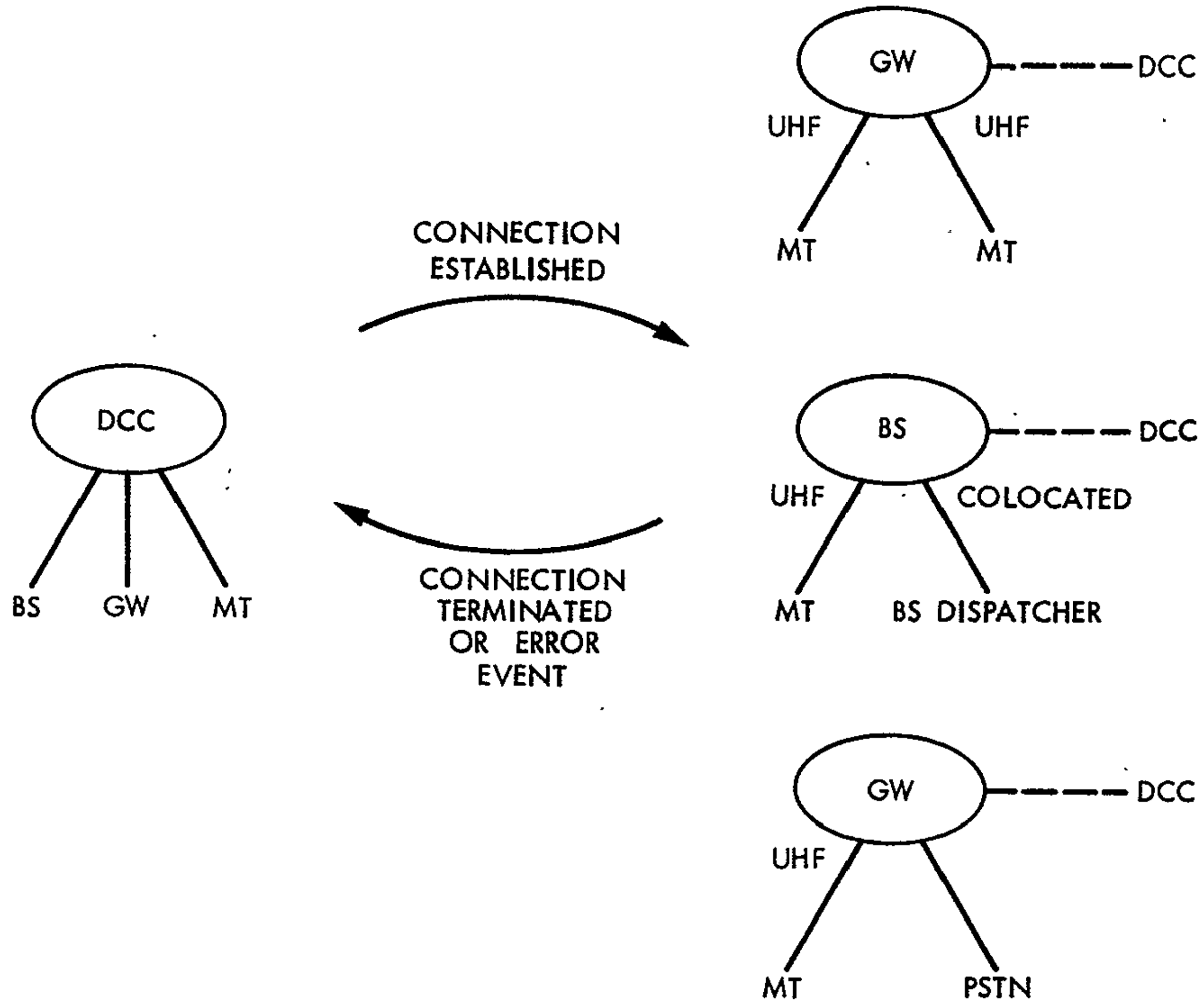


Figure 4-3. Intragroup Control Topology

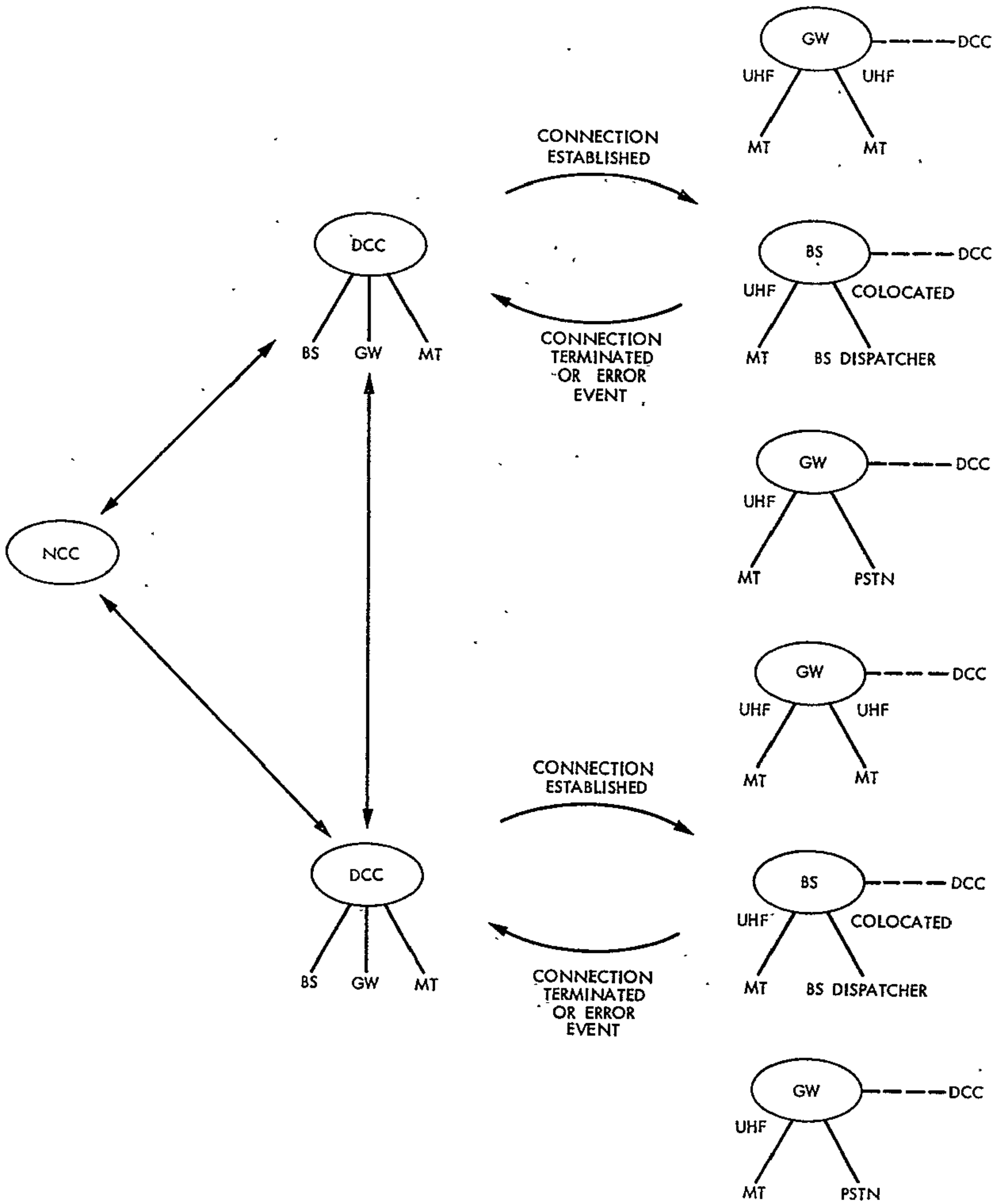


Figure 4-4. Intergroup Control Topology

4.1 NETWORKING SCHEME

MSAT-2 employs a 7-frequency reuse scheme. The assumed allocation of 10 MHz is divided into 7 equal frequency subbands of 1.43 MHz each. Each of the multiple beams is assigned to operate in one of these subbands. Signals in each UHF beam are translated to a unique part of the Ku beam as described in Chapter 3. There are approximately 170 to 210 channels per beam for the east and west satellites, respectively. For convenience, the number of channels per beam is taken to be N in the following discussion.

4.1.1 Networking Algorithm Concept

Figure 4-5 shows the conceptual protocol for the intragroup communications of MSAT-2. There are N_r reservation channels, N_v voice channels, and N_d data channels such that $N_v + N_d + N_r = N$. In the following discussion "message" refers to either voice or data. Whenever an MT initiates a transmission, it monitors a status channel to find out the identities of the currently assigned reservation channels. It then sends a request in one of the reservation channels to the central controller (CC) that controls the current beam. The request consists of the origin and destination addresses, whether it is a voice or data request, and, in the case of a data request, the length of the data message. After the MT transmits a reservation request, it waits for a positive acknowledgment from the CC. If a positive acknowledgment is not received within a certain time period, the MT will retransmit the request after a random delay. Each reservation channel is a pure ALOHA random-access channel.

The CC resides at the DCC and is responsible for assigning the voice and data channels to reservation requests generated by the MT's. For data channels, it keeps track of how long each customer has been in service at each channel

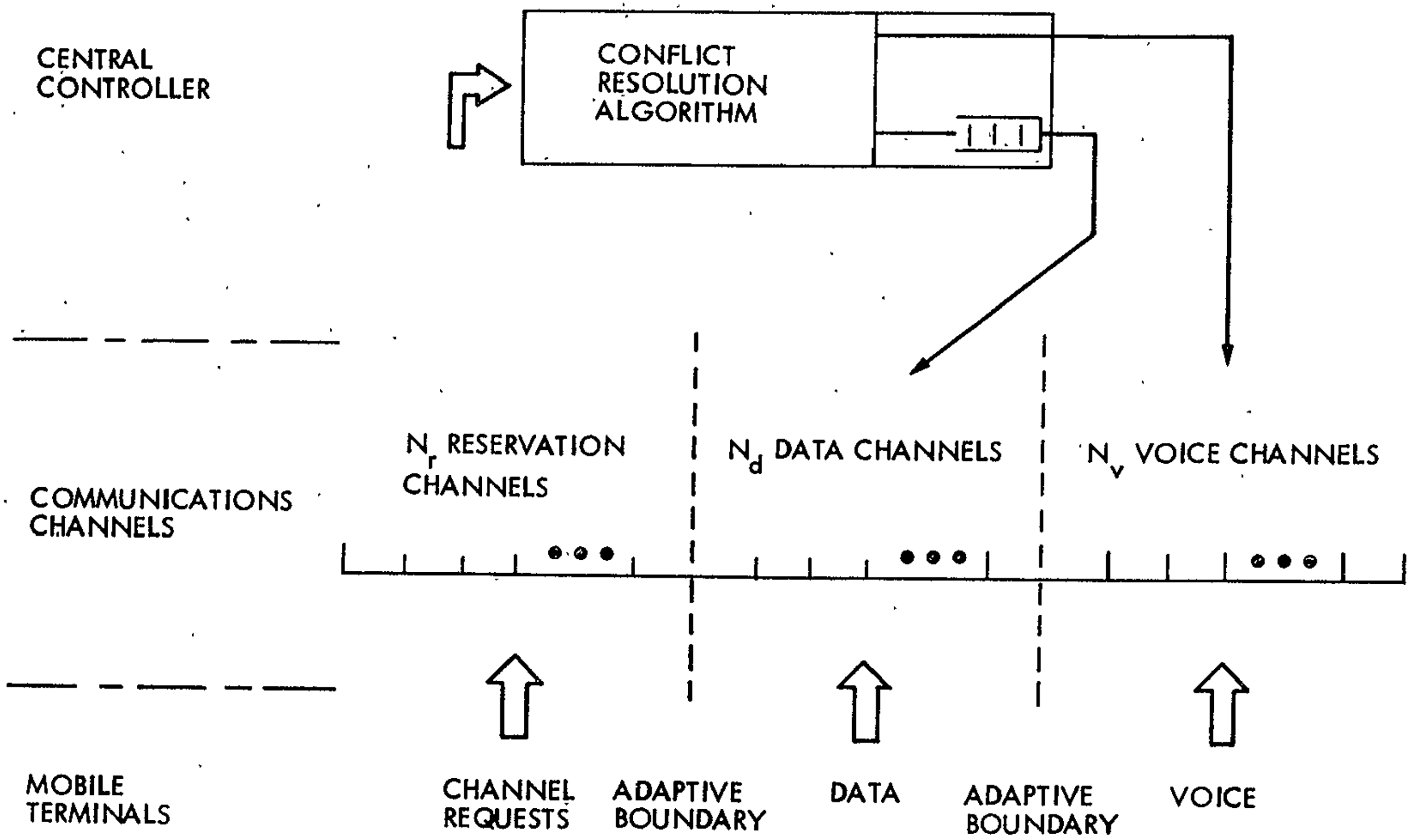


Figure 4-5. Protocol for Intragroup Communications

and how many requests are waiting to get served. The CC can then estimate, at any point in time, what the backlog is at each data channel. For voice channels, it monitors which channels are busy.

Intergroup communications will be accomplished in two steps. Once a connection request from the MT is accepted by the corresponding DCC, the DCC will deliver this connection request information to the NCC. The NCC will notify the destined DCC to page the destined MT. After the destined MT acknowledges the connection request, a call will be set up between the DCC's. Only network control information will be routed to the NCC for accounting purposes.

4.1.2 Generic Data Communications

When a reservation request for a data transmission arrives successfully at the CC from an MT,the CC assigns the message to the channel with the smallest backlog, calculates how long it takes before this channel has finished its backlog, and sends an acknowledgment message to the mobile terminal. It is assumed queueing and transmission delays on the acknowledgment channel (the return channel)are negligible compared to the propagation delay. The acknowledgment message contains the identity (ID) of the MT, the ID of the assigned channel, and a holding time denoted by d_H.

The MT will initiate a transmission at the assigned message channel d_H seconds after receipt of the acknowledgment message. The value of d_H is calculated (taking into account the propagation delays) such that if there is any waiting request at the CC, a previously busy channel will be made available to this waiting request as soon as it becomes open.

4.1.3 Generic Voice Communications

When a reservation request for a voice call arrives successfully at the CC from an MT, the CC assigns the call to one of the available voice channels, and sends an acknowledgment message to the MT. Note that for two-way voice communications, voice channels are assigned in pairs, one from the forward channels and one from the return channels. It shall be assumed that whenever a voice channel is available in the UHF-to-Ku direction, a voice channel will also be available in the Ku-to-UHF direction. Therefore, the analysis given in section 4.2.1 only considers the channels in the UHF-to-Ku direction. The acknowledgment message contains the ID of the MT and the ID's of the assigned channels. A voice request which arrives when all the voice channels are busy will be ignored, and assumed lost from the system.

The channel allocation N_r:N_v:N_d is an important performance parameter. The CC dynamically reassigns voice, data, and reservation channels to minimize the blocking probability of the voice traffic and the total average delay of the data traffic. In order to do this, the CC estimates S_v and S_d, the total voice and data generation rates, by keeping track of the number of successful requests which have arrived in some recent interval. Using results derived in 4.2, the CC can determine, for a given S_v and S_d, optimal allocation. The CC must inform the MT's of all channel reassignments. To ensure that an MT will not be accessing an obsolete reservation channel, reassignments will only be activated after a certain waiting period, typically one round-trip propagation delay.

4.2 PARAMETRIC COMPUTATIONS OF SYSTEM CAPACITY

The performance of this multiple access scheme will now be analyzed. It will be described how to obtain the optimal channel allocation for different voice and data generation rates and determine the maximum traffic levels that can be supported under a certain delay requirement for data messages and a certain blocking probability for voice calls.

4.2.1 Model Assumptions

The following assumptions will be made in the analysis:

(1) The MT's collectively generate Poisson data traffic at S_d messages/second and Poisson voice traffic at S_v calls/second.

(2) Each MT randomly chooses to access one of the N_r reservation channels for either a voice call or a data transmission.

(3) Each MT holds one and only one active data message or one active voice call at any time, but not both.

(4) Successful reservation requests arrive at the CC in a Poisson manner with a rate of $S_v + S_d$.

(5) The retransmission delay is uniformly distributed between 0 and K seconds.

(6) Both data and voice channels are assigned on a first come, first served basis. Voice channels are blocked calls cleared.

(7) Reservation, message, and acknowledgment channels are error free.

(8) Processing delays at the CC and the MT's are negligible.

(9) The data messages are of fixed lengths.

(10) The duration of voice calls are exponentially distributed.

Assumption (4) is necessary to simplify the analysis of the data channel delay. It has been shown that this assumption gives a fairly good approximation. Detailed analysis and simulation are given in [3].

4.2.2 Performance Analysis

4.2.2.1 Reservation Channel Delay. For each reservation request, the probability that a transmission is successful is S/G, where S is the throughput and G is the channel traffic. Therefore, the expected number of unsuccessful transmissions per successful reservation is (G/S - 1). Each unsuccessful transmission, on the average, incurs a delay of $(t_o + K/2)$ seconds where t_o is the timeout period, measured from the start of the transmission. The successful transmission takes time, $(d_p + \tau)$ seconds, to reach the CC, where τ is the reservation-request transmission time and d_p is the propagation delay from an MT to the CC or vice versa. Hence, the total average reservation delay is given by [4]

$$d_r = (t_o + K/2)(G/S - 1) + d_p + \tau \tag{4-1}$$

or

$$d_r = (t_o + K/2)\ (e^{2G\tau} - 1) + d_p + \tau$$

4.2.2.2 Data Channel Delay. Figure 4-6 shows the chronological sequence of events corresponding to the transmission of acknowledgment and data messages. At times t_1, t_2. . ., t_n reservation requests for messages M_1, M_2,. . ., M_n arrive successfully at the CC. Since the queueing and transmission delays on the return channel (CC to MT) are negligible compared to the propagation delay, the corresponding acknowledgment messages will arrive at the MT's at times d_p seconds later. Therefore, the acknowledgment message arrival process at the MT's (global queue in the sky) is identical to the arrival process of the

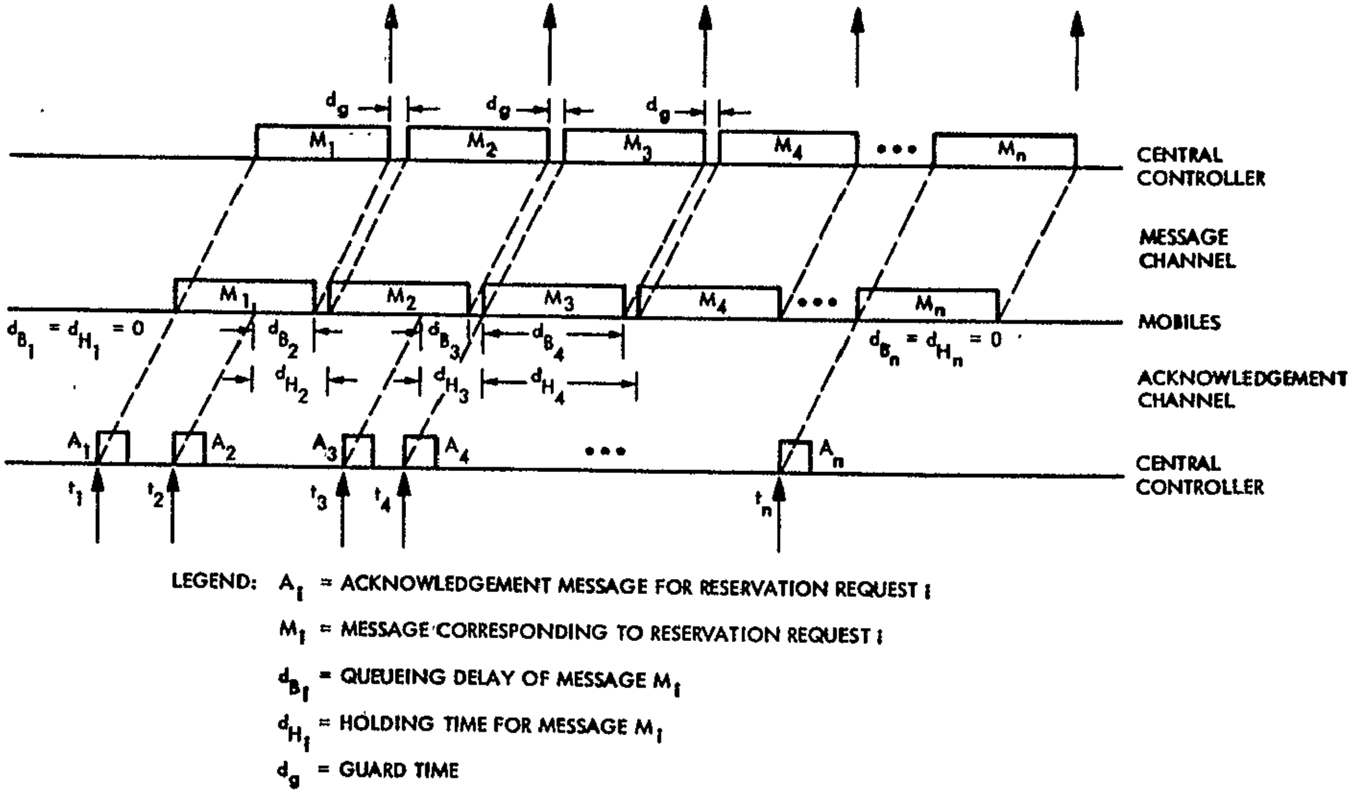


Figure 4-6. Chronological Events Corresponding to the Transmission of Acknowledgment and Data Messages

reservation requests at the CC, except for a time shift of d_p seconds. Upon receipt of an acknowledgment message, an MT must hold for a time period d_H before it can initiate its own transmission. It was shown in [5] that this queueing discipline is equivalent to an M/D/s system. Therefore, the total average data message delay D is given by

$$D = d_r + d_B + d_g + d_T + 2\,d_p \tag{4-2}$$

where

d_B = average queueing delay for the message in the global queue

d_g = guard time

d_T = transmission delay of the message on the satellite data channel

and the last term corresponds to the propagation delay on the acknowledgment and data channels. The term d_B is the queueing time of an M/D/s queue where the service time is $d_T + 2\,d_g$ and is evaluated using the approximation given in [Ref. 6], where the d_g is required to accommodate the propagation delay difference from the satellite to MT's on different ends of the satellite's beam coverage. (Numerical results contained in [6] show that the maximum error is 3%.) Therefore,

$$d_B = 0.5\,W_d/N_D(s) \tag{4-3}$$

where W_d is the queueing delay of the equivalent M/M/s queue and $N_D(s)$ is the normed cooperation coefficient given in [6].

4.2.2.3 Voice Channel Blocking Probability. The analysis of the voice channels is different from that of the data channels because voice calls are of random durations and there is no queue for the voice channel requests. Therefore, the CC cannot send a holding time parameter d_H ahead of time to the MT's. In fact, the CC cannot assign an occupied channel for any other purpose until either side of the conversation hangs up and the status change reaches the CC. Therefore, a total of 2 d_p seconds is wasted for each channel assignment. Figure 4-7 shows a typical sequence of events corresponding to the transmission of acknowledgment on the return channel and voice calls on one particular voice channel. At times t_1, t_2,. . ., t_n reservation requests for calls C_1, C_2,. . . , C_n arrive successfully at the CC. Since the queueing and transmission delays on the return channel are negligible compared to the propagation delay, the corresponding acknowledgment messages will arrive at the MT's at times d_p seconds later. If there is a voice channel available, a channel assignment will be sent along with the acknowledgment message. The MT will tune to the assigned channels for conversation. Otherwise, a channel-busy status message will be sent along with the acknowledgment message. The caller must then redial. Therefore, any successful voice request will hold the channel for an average of $(2 d_p + d_g + 1/\mu_v)$ seconds, where $1/\mu_v$ is the average call duration. This is an M/G/s/s, s-server loss system, in which a blocked call will be cleared from the queueing system. It has been shown [7] that the blocking probability depends only on the mean of the service time. Therefore, the blocking probability of an s-channel system is given by Erlang B-loss formula [8].

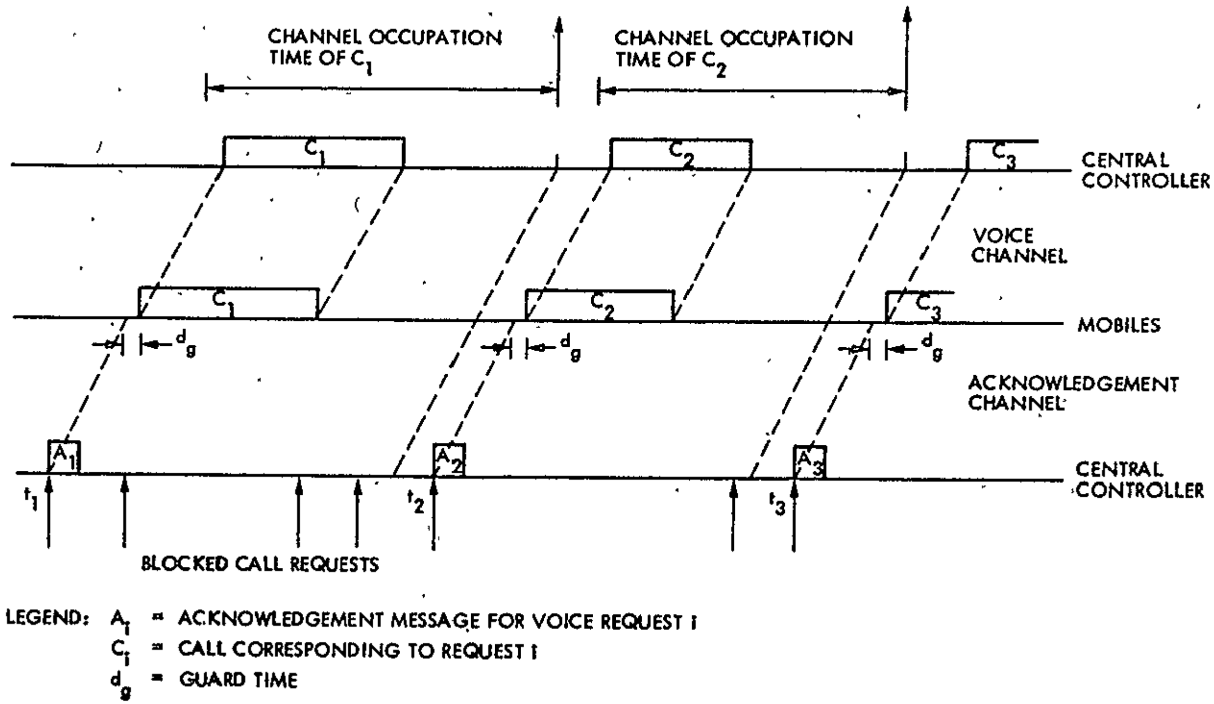


Figure 4-7. Chronological Events Corresponding to Voice Calls and the Transmission of Acknowledgment Messages

In the next section, the behavior of the total average message delay D and the blocking probability P_B as a function of the total input traffic $S_v + S_d$ and the channel allocation $N_r:N_v:N_d$ will be studied.

4.2.3 Numerical Results

The maximum throughput of a pure ALOHA channel is $1/(2\tau e)$, where τ is the transmission time for reservation requests [9]. Therefore, for stability purposes, the number of reservation channels $(N_r)_{min}$ must satisfy

$$(N_r)_{min} = 2\tau e\,(S_v + S_d) \tag{4-4}$$

For a stable $M/D/N_d$ queue corresponding to the data channels, message channel utilization must be less than unity, i.e.,

$$S_d\,(d_g + d_T)/N_d \leq 1 \tag{4-5}$$

Defining $\Omega = d_g/\tau$ as the guard time ratio, (4-5) can be written as

$$(N_d)_{min} = S_d\,\tau\,(\Omega + \alpha_d) \tag{4-6}$$

where α_d is the ratio of the message length to the reservation packet length.

For a stable $M/G/N_v/N_v$ queue corresponding to the voice channels, voice channel utilization must be less than unity, i.e.,

$$S_v\,(1/\mu_v + 2\,d_p + d_g)/N_v \leq 1 \tag{4-7}$$

Defining α_v as the ratio of the average call duration to the reservation packet transmission time, (4-7) can be written as

$$(N_v)_{min} = S_v\,\tau\,(\Omega + 2d_p/\tau + \alpha_v) \tag{4-8}$$

Since the total number of available channels is N,

$$(N_r)_{min} + (N_d)_{min} + (N_v)_{min} \leq N \tag{4-9}$$

The trade-offs between the maximum normalized throughput between voice and data mobile users can be plotted as a function of the average voice call duration. Figure 4-8 shows the theoretical maximum usage that can be supported by MSAT-2.

Currently planned channel spacing for MSAT-2 is 5 kHz. It is assumed that a total of 150 channels will be available. To reduce the effect of adjacent channel interferences in the fading environment, the allowable data rate is 2.4 kbps. It is assumed that the reservation packet is 120 bits long and the average message packet length is 1000 bits. The propagation delay d_p is taken to be 250 mS and the guard time d_g is 16 mS. For the reservation channels, it is assumed that t_0 = 600mS and K = 15 τ. Also, a maximum 2% blocking probability for voice calls and an average call duration of 90 s are assumed.

In Figure 4-9, the average data delay D versus $\alpha = N_r/N_d$ for different data and voice call arrival rates is plotted. Note that at each traffic level, there is a ratio α^* which minimizes the delay. This optimal ratio decreases as the traffic increases. That is, in heavy traffic, some reservation channels shall be closed up in order to decrease the number of successful reservation packets, while at the same time increasing the number of message channels to expedite clearing up the backlog.

In Figure 4-10, the average data delay D versus the data arrival rate S_d for different voice call arrival rates at the optimal ratio α^* is plotted. As the voice call arrival rate increases, the amount of data traffic that can be supported decreases substantially, and the delay increases.

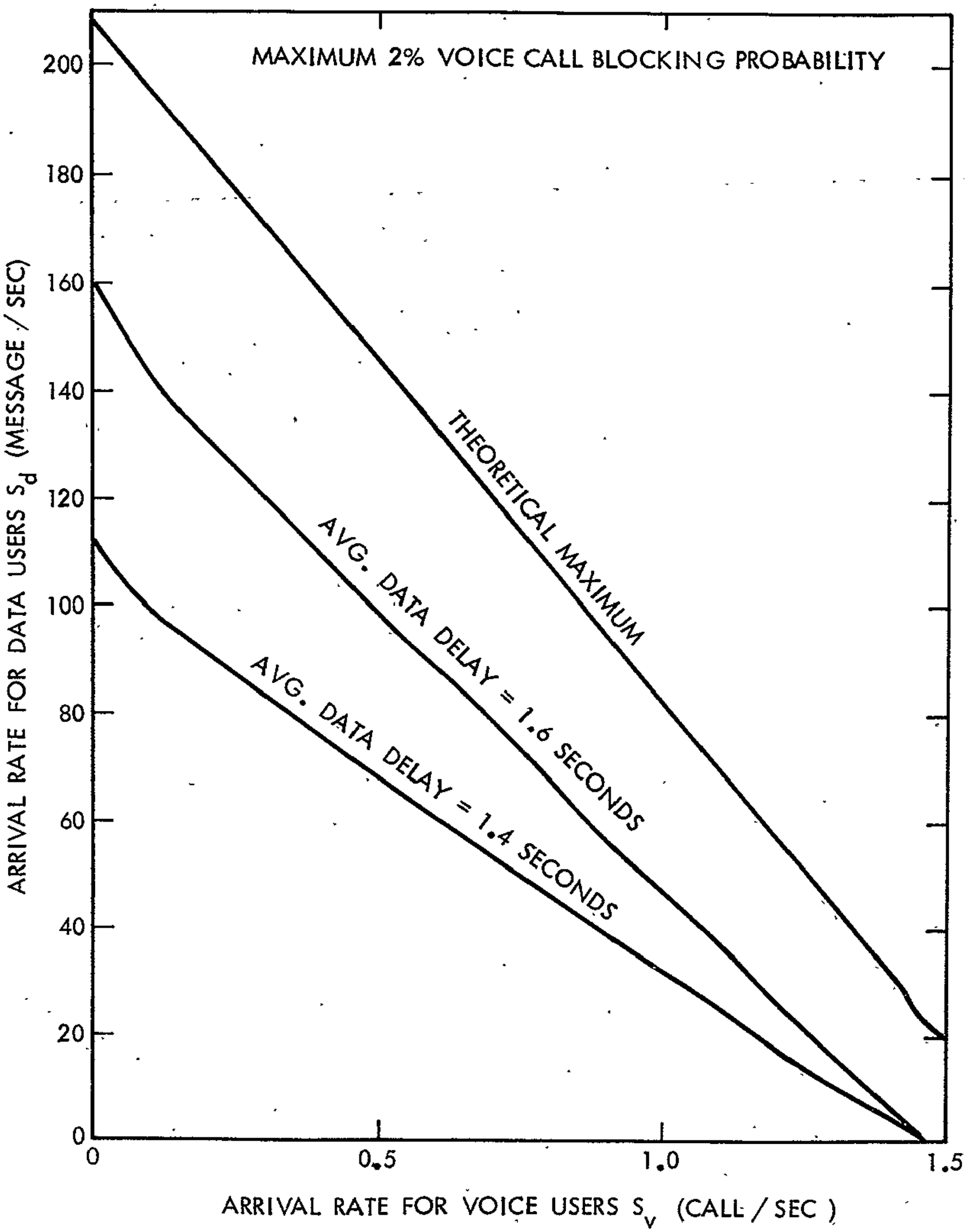


Figure 4-8. Trade-Off Between Voice and Data Traffic

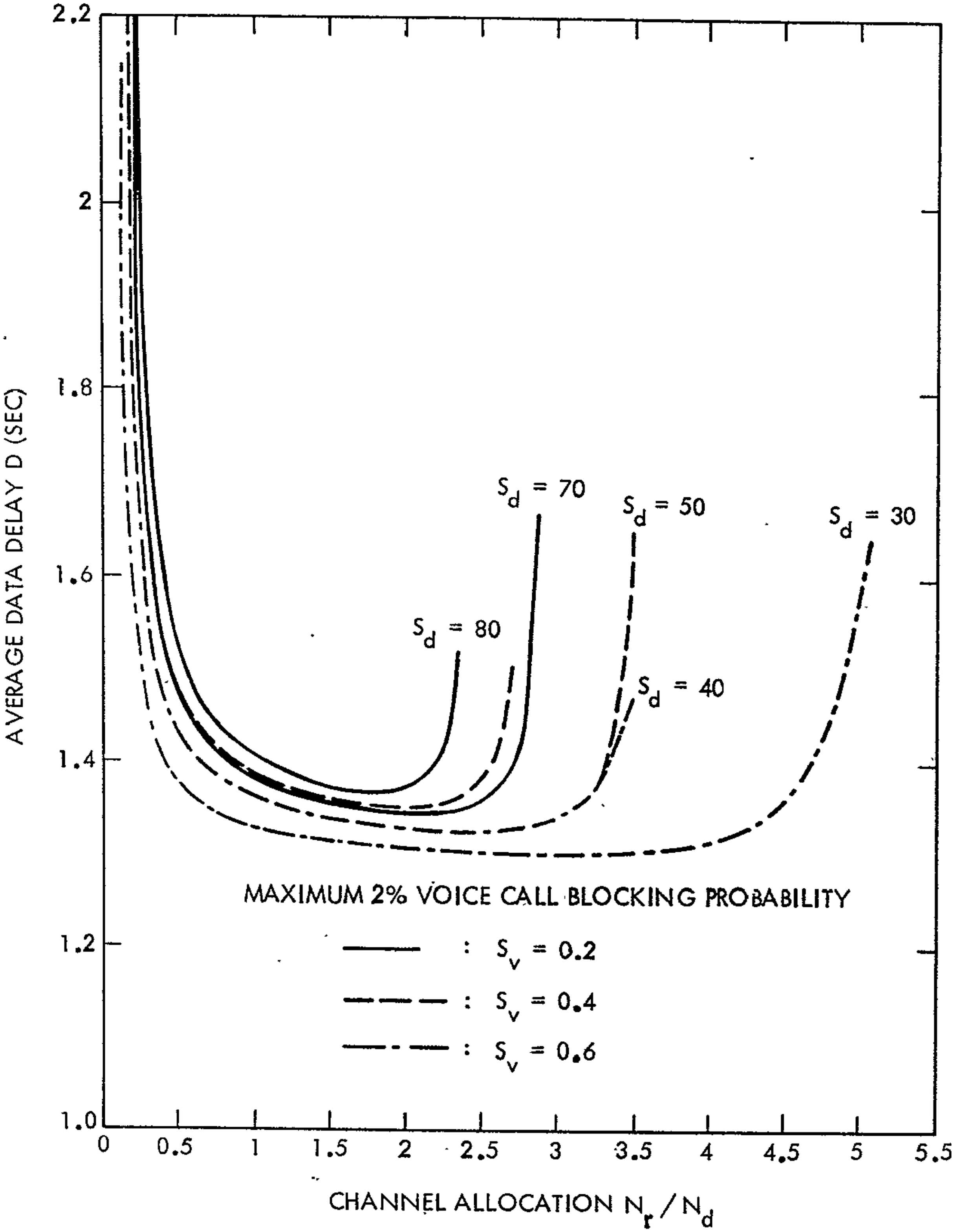


Figure 4-9. Average Data Delay Versus Channel Allocation Ratio

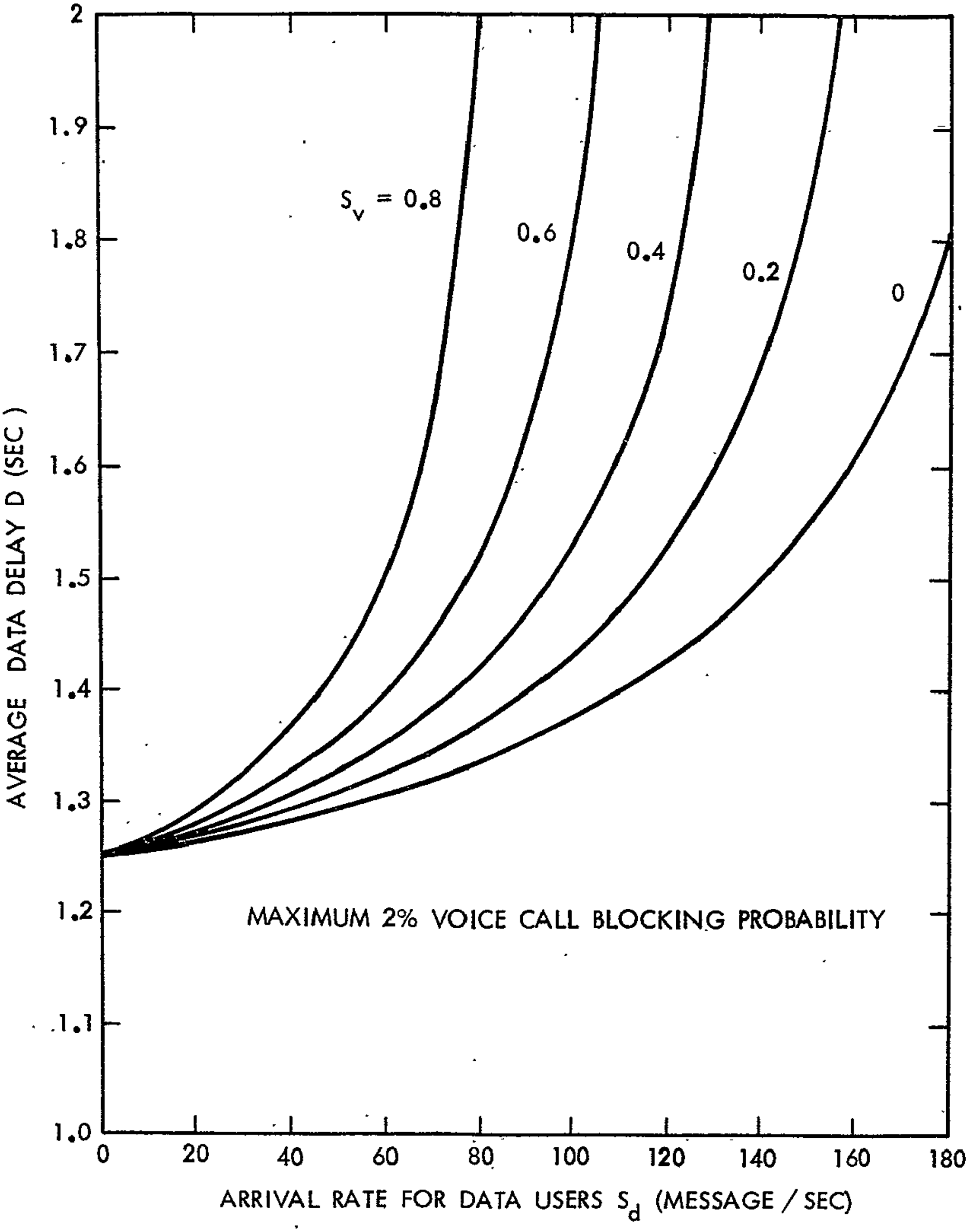


Figure 4-10. Average Data Delay Versus Data Arrival Rate

In Figure 4-11, the optimal channel allocation ratio α* versus the data message arrival rates for different voice call arrival rates is plotted. This figure is useful to the CC when it becomes necessary to reallocate the channels. The CC estimates S_d and S_v, the current data and voice call arrival rates, by observing the number of successful reservation requests in a recent period. Using S_v and the Erlang B-loss formula stated in [8], the CC finds the number of voice channels required to satisfy the blocking probability requirements. It can then find the optimal channel allocation ratio from Figure 4-11.

In Figure 4-8, a trade-off between the data and voice call arrival rates under the 2% voice-call blocking probability constraint for different data message delay requirements is also studied. For example, if the voice call arrival rate is 0.4 call/sec, then the data arrival rate must be less than 75.58 message/sec in order to have a data message delay of less than 1.4 seconds. Assuming that an MT generates on the average one data message or one voice call per hour, this means that to support 272,088 data users, the number of voice call users is at most 1,440.

Finally, in Figure 4-12, the average number of users that a channel can support under the 2% voice-call blocking probability and the 1.4 sec average data-delay constraints versus total number of available channels for various ratios of the number of voice call users to that of data users is shown. In this figure, it is assumed that an MT generates on the average one data message or one voice call per hour. The result characterizes the service capability of the system.

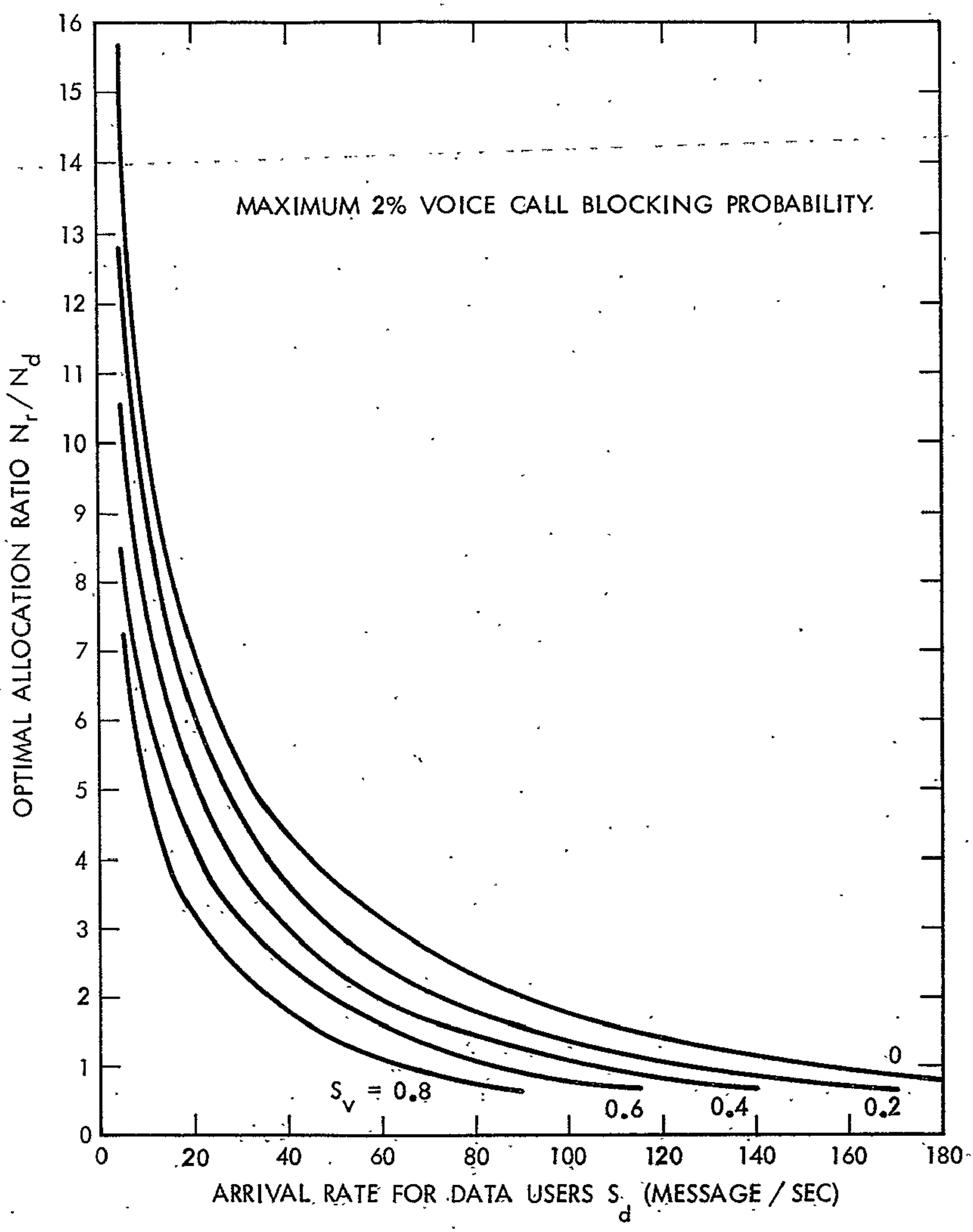


Figure 4-11. Optimal Channel Allocation Ratio Versus Data Arrival Rate

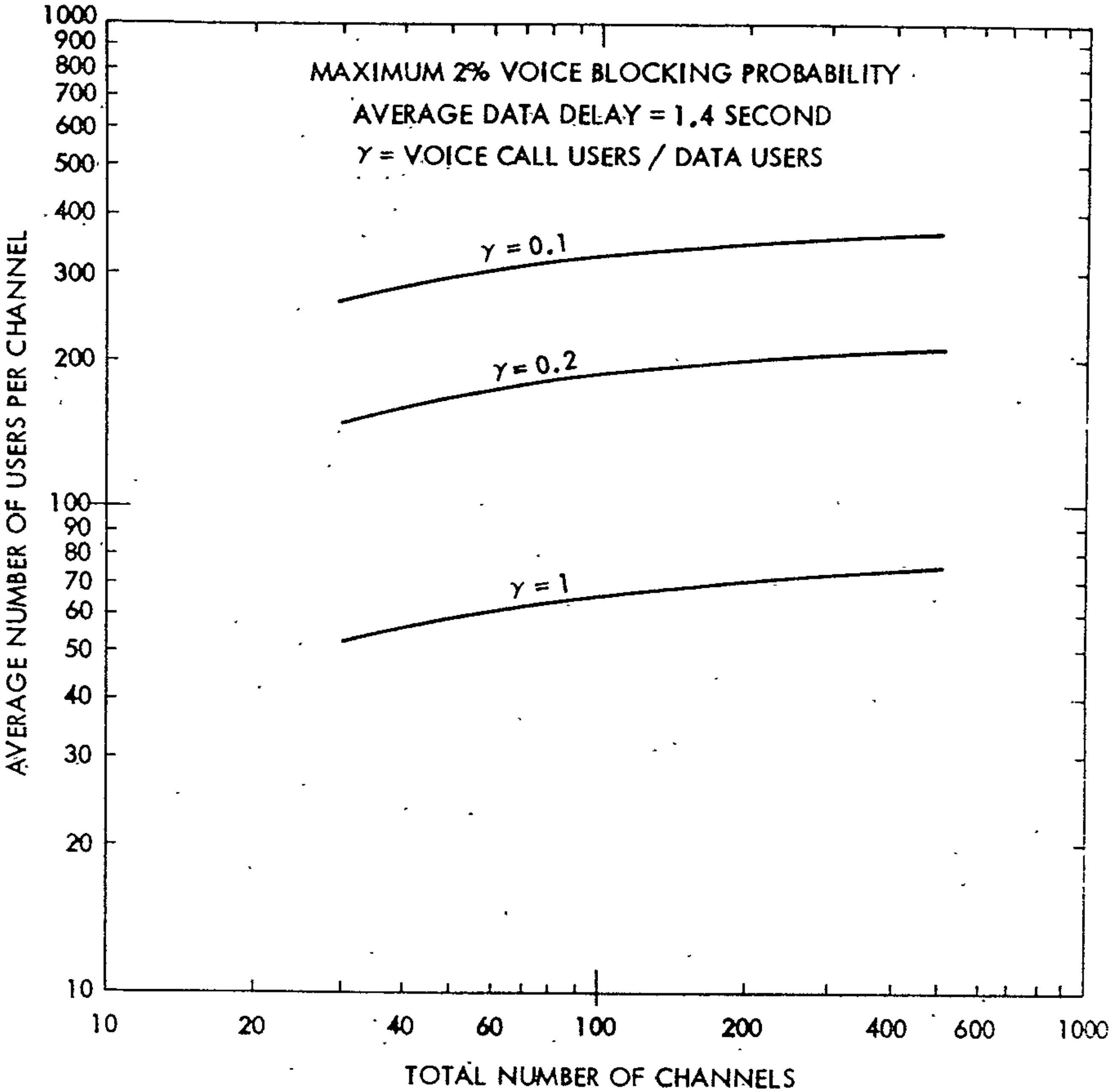


Figure 4-12. Users Per Channel Versus Total Number of Channels

REFERENCES

1. Knouse, G. H. and P. A. Castruccio, "The Concept of an Integrated Terrestrial/Land Mobile Satellite System," IEEE Trans. on Veh. Tech., Vol. VT-30, No. 3, August 1981, pp. 97-101.

2. Anderson, R. E., R. L. Frey, and J. R. Lewis, "Technical Feasibility of Satellite-Aided Land Mobile Radio," Proc. International Conference on Communications, June 1982, pp. 7H2.1-7H2.5.

3. Clare, L. P. and T. Y. Yan, "The Interdeparture Time Distribution of a pure ALOHA channel with Arbitrary Renewal Arrival Process," Proc. GLOBECOM'84, Nov. 1984, pp.35.5.1-35.5.5.

4. Lam, S. S., Packet Switching in a Multiaccess Broadcast Channel with Applications to Satellite Communication in a Computer Network, Technical Report UCLA ENG-7429, April 1974.

5. Li, V. O. K. and T. Y. Yan, "Adaptive Mobile Access Protocol (AMAP) for the Message Service of a Land Mobile Satellite Experiment (MSAT-X)," IEEE Trans. on Selected Areas in Communication, Vol. SAC-2, NO. 4, July 1984, pp. 621-627.

6. Boxma, O. J., J. W. Cohen, and N. Huffels, "Approximations of the Mean Waiting Time in an M/G/S Queueing System," Operations Research, Vol. 27, No. 6, Nov.-Dec. 1979, pp. 1115-1127.

7. Gross, D. and C. M. Harris, Fundamentals of Queueing Theory, John Wiley and Sons, 1974.

8. Kleinrock, L., Queueing Systems, Volume 1, John Wiley and Sons, 1976.

9. Abramson, N., "Packet Switching with Satellites," Proc. Nat. Comput. Conf. AFIPS, Vol. 42, 1974, pp. 695-702.

CHAPTER 5

AN L-BAND SYSTEM

5.0 INTRODUCTION

The 20-m baseline system is designed to operate in the UHF frequencies. The UHF and L-band are two of the frequency bands considered for a mobile satellite system. It is well known that, for a given antenna size, the gain of the antenna increases as the square of the operating frequency, assuming that the same surface accuracy and efficiency can be maintained. Without going into a detailed trade-off and antenna sizing, a quick examination of a few possible L-band configurations will be presented in this chapter, using a 10-m antenna for the satellite. The configurations are shown in Table 5-1.

The payload weight, payload power, the system capacity, and the user cost will be presented and compared to the baseline UHF system.

5. 1 STUDY ASSUMPTIONS AND APPROACH

The first step in examining L-band configurations is to estimate the payload weight of the L-band system using the payload weight model in Appendix D, with appropriate modifications to account for the difference between the L-band and UHF communications payload. Once the payload weight is determined, the payload power will be estimated using the curve in Figure 2-7. The capacity of the system will then be calculated and compared to the UHF baseline design.

Table 5-1. Possible L-Band Configurations

Configurations	Satellite Antenna Size, m	Mobile Antenna Gain, dBi
1	10	10
2	10	13
3	10	16

To facilitate the study and for the purpose of simplicity, the design of the L-band system is assumed to be basically the same as the UHF system. Specifically, both systems are assumed to be the same in the following areas:

1. The number of satellites and their locations.
2. The deployed configuration and the stowed configuration, with the physical dimensions appropriately modified.
3. The design of the antenna feed, i.e., one-element design.
4. The design of the transponder, including the translation from the backhaul link to the service link, and vice versa.
5. The backhaul frequency, required E_B/N_O, coverage area, multipath, allocated bandwidth, frequency reuse factor, channel spacing, etc.

The areas of difference between the two systems are:

1. The size of the satellite antenna.
2. The gain of the mobile antenna. (The mobile-antenna gain will be treated parametrically for the L-band design. In the UHF design, the gain has been fixed at 10 dBi).
3. The service link frequency. (The L-band frequency is given in Chapter 1, and is approximately twice the UHF frequency.)

In the design of the UHF system, several tradeoffs were performed to select the size of the satellite antenna. Without going through the necessary trade-off studies, a 10-m antenna will be used for the L-band design. Although the 10-m antenna may not be an optimal choice, the proper antenna size is believed

to range from 10 m to 15 m, using the baseline satellite bus. The capacity for a 10-m and a 15-m satellite is not expected to be much different using the same baseline bus. A 20-m satellite, which would have about 80 beams, would probably be too heavy for the baseline bus. A 5-m satellite would probably have much fewer channels than a 10-m satellite.

5.2 THE NUMBER OF MULTIPLE BEAMS AND THE OVERALL C/I

The payload weight is tied to the number of multiple beams. Before one can estimate the payload weight using the model in Appendix D, it is necessary to determine the number of beams. Since the L-band antenna is one-half of the size of the UHF antenna, and since the L-band frequency is about twice the UHF frequency, the antenna pattern, beamwidth, the gain, and the number of multiple beams are, therefore, roughly the same. (It is noted that an L-band antenna properly scaled from the 20-m UHF antenna would have a diameter of 10.6 m instead of 10 m, as shown in Chapter 2.) Specifically, the east satellite will probably have 24 beams, and the west 21 beams. To further simplify the study, only the east satellite will be considered in the rest of this chapter.

Because the L-band satellite antenna is a scaled version of the UHF antenna, the interbeam isolation is about the same as the UHF case for the same frequency reuse scheme. Assuming the intersatellite isolation and the intermod isolation are both the same as the UHF system, the overall C/I, which is an important parameter in determining the power requirement, should therefore be the same as the UHF baseline design.

5.3 ESTIMATED PAYLOAD WEIGHT AND PAYLOAD POWER

The payload weight of the 10-m satellite can be estimated using the payload weight model in Appendix D. The estimated weight is approximately 344 kg, of which the antenna accounts for 140 kg, the feed assembly and the rest of the transponder make up the remaining 204 kg. The available payload power is approximately 2700 watts using the curve in Figure 2-7. This power level is based on 100% eclipse power and a full north-south station-keeping. Since the UHF baseline design requires only 50% eclipse capability and ± 2-degree station-keeping, the L-band design will assume the same. Reducing the eclipse capability to 50% increases the amount of available payload power. The amount of increase varies according to the operating power level. At the 2700-watt level, the increase is approximately 1000 watts. The weight savings due to a reduced north-south station-keeping can be used to generate another 850 watts to the payload according to Table 2-18. This would result in a payload power of 4550 watts.

Operating the communications payload at 4550 watts would generate a heat load of approximately 3400 watts. This amount of heat dissipation exceeds the projected capability of the thermal subsystem of the baseline bus, which is estimated to be capable of handling up to 2100 watts of heat dissipation for the communications payload. To dissipate the additional heat, it would be necessary to modify the existing thermal subsystem by adding more heat pipes and radiators, both of which would increase the weight of the thermal subsystem. To adequately handle the amount of heat dissipation, an increase of approximately 12 kg for the thermal subsystem is estimated. To accommodate the added thermal subsystem weight, the power subsystem will have to be reduced by the same amount, resulting in a power reduction of approximately 110 watts

(9.2 W/kg • 12 kg = 110 watts). The available payload power, after being adjusted for the effects on the thermal subsystem, is 4440 watts.

5.4 POWER BUDGETS AND THE NUMBER OF SATELLITE CHANNELS

The satellite for the three configurations listed in Table 5-1, is the same satellite having a 10-m antenna, 344 kg of communications payload, and 4440 watts of payload power. Because the mobile antenna is different for these configurations, the required power per channel is different. Consequently a different power budget is required for each of the three configurations.

The receiver/translator, upconverters, and downconverters consume a total of 330 watts of power. Allowing 260 watts for margin, which is about 6% of the total payload power, the power available for the L-band transmitter and the Ku-band transmitter together is 3850 watts. This power will be appropriately divided between the Ku-band and L-band transmitters according to the per-channel power requirement.

The per-channel power required for the backhaul link for the three L-band configurations is 0.0065 watts, the same as the baseline UHF system.

The per-channel power requirement for the service link will be based on the baseline design, assuming that overall C/I is the same for the L-band and the UHF systems.

The per-channel power for the first configuration, which employs a 10-dBi mobile antenna, will be a factor of 4 higher than that of the baseline system, due to the increased space loss. The baseline design requires 0.129 watts/channel, as indicated in the link tables in Chapter 3. The required power for the first configuration is thus 0.516 watts per

channel. In configuration 2, the mobile-antenna gain is 3 dB, or a factor of 2, higher than that of the first configuration. The power required is thus 0.258 watts/channel. In configuration 3, the mobile antenna gain is 6 dB, or a factor of 4, higher than the 10-dBi antenna in the first configuration. The required power is thus lower by a factor of 4 or 0.129 watts/channel.

The power budget for the three configurations is shown in Table 5-2.

The per-beam power, per-channel power, and the number of satellite channels are shown in Table 5-3. An overall DC-to-RF efficiency of 26% has been assumed in the calculation of RF power.

Based on the available power, the number of channels is approximately 1900, 3800, and 7400 channels per satellite for the first, second, and third configurations, respectively. Because of the limited spectrum, the number of channels is limited to 6857 for the west satellite, and 6000 for the east satellite, as indicated in Chapter 2. Configuration 3 is thus frequency-limited. The total system capacity, i.e., the number of satellite channels for the east and west satellites combined, is approximately 3800, 7600, and 12,857 channels for the three L-band configurations.

5.5 ESTIMATED NUMBER OF USERS AND USER MONTHLY COST

The number of users that can be supported by a system depends on the voice-to-data user ratio, as previously mentioned. Assuming a value of 0.2 for this ratio, the number of users is estimated to be 350,000, 750,000, and 1,300,000. If the voice-to-data user ratio goes down to 0.1, the number of users increases to 0.6, 1.3, and 2.3 million. In the estimation of

Table 5-2. Payload Power Budget

	Configuration 1	Configuration 2	Configuration 3
Satellite Antenna Size, m	10	10	10
Mobile Antenna Gain, dBi	10	13	16
Power Budget, watts			
L-band HPA	3802	3755	3666
Ku-band HPA	48	95	184
Receiver/Translator	300	300	300
Upconverter/Downconverter	30	30	30
Margin	260	260	260
Total	4440	4440	4440

Table 5-3. Summary of RF Power and Satellite Channels

	Configuration 1	Configuration 2	Configuration 3
L-band RF Power, watts			
Total Power	989	976	953
Per-Beam Power	42.3	41.7	40.8
Per-Channel Power	0.516	0.258	0.129
Number of Channels	1900	3800	7400
Ku-band RF Power, watts			
Total Power	12	25	48
Per-Beam Power	12	25	48
Per-Channel Power	0.0065	0.0065	0.0065
Number of Channels	1900	3800	7400(1)
Total Number of Channels for Two satellites	3800	7600	14800(1)

NOTE:

(1) Assuming a 7-frequency reuse and a 10-MHz allocation, the number of channels that can be supported by the available spectrum is 6857 channels per satellite as indicated in Table 2-13.

the number of users, the number of satellite channels has been reduced by a factor of 2 to account for the skewed user population, as previously mentioned.

It is obvious from the previous discussion and from Table 5-2 that the number of channels and the number of users, for the 10-m L-band system, are substantially less than those of the 20-m UHF system for the same mobile-antenna gain. There is, however, a financial advantage that the 10-m L-band system has over the UHF system. The 20-m reflector is a significant cost item in the baseline system simply because of its size. Replacing the 20-m antenna with a 10-m reflector, a significant savings can be obtained. Based on available data [1], the 10-m satellite is estimated to cost \$3 M less than a 20-m satellite, using the same baseline bus. For a system with three satellites, the savings add up to \$9 M.

The 10-m L-band system would reduce the cost of the launch service, which accounts for a significant part of the system cost. It is estimated that the 10-m satellite can be launched with a stowed length of 1/4 to 1/3 of the length of the STS cargo bay. Assuming an occupied length of 1/3 of the cargo bay, the launch cost is estimated to be \$46 M in 1985 dollars for a 1992 launch. Compared to the launch cost of \$55 M for the 20 m satellite, this represents a savings of \$9 M per launch. With three launches, the total savings is \$27 M.

The estimated costs for the space segment and the ground segment are shown in Table 5-4 for the three L-band configurations. The costs of the baseline system are also included for comparison. The costs of the ground segment for the L-band configurations have been scaled from the UHF baseline data according to their projected capacities.

Table 5-4. Estimated Costs for the Three L-Band Configurations

	Baseline UHF System	L-Band System Conf. 1	L-Band System Conf. 2	L-Band System Conf. 3
Satellite Antenna Size, m	20	10	10	10
Mobile Antenna Gain, dBi	10	10	13	16
Channels/Satellite	4300	1900	3800	7400
Estimated Cost, in 1985 Dollars				
Space Segement (3 Satellites)	501M	459M	459M	459M
Ground Segment	79M	49M	74M	100M
Space Segment and Ground Segment Combined	580M	508M	533M	559M
Estimated user Monthly Cost (1)(2)	20	35	20	15
Mobile Terminal Cost	45	45	45	45
Total Monthly Cost	65	80	65	60

Note:

(1) The cost of the mobile equipment is not included.
(2) The estimated cost is based on an operating cost of $.05/minute and 100 call-minutes per month.

Due to a lower satellite cost and lower launch cost, launch insurance would be lower for the 10-m L-band satellite. A reduction of $6 M in launch insurance is estimated. The total savings on the space segment is thus approximately $42 M.

The estimated user monthly cost, which is also shown in Table 5-4, is $35, $20, and $15 for configurations 1, 2, and 3. Compared to the estimated cost of $20 for the baseline system, which uses a 20-m satellite antenna and a 10-dBi mobile antenna, the user cost for the L-band system is higher if the mobile antenna gain is to remain at 10 dBi. If the gain is allowed to increase to 13 dBi, the user cost for the L-band would be about the same as that of the UHF system. If the gain is further increased to 16 dBi, the L-band user cost would be lower than that for the UHF system by 30%.

The user monthly cost is based on a usage of 100 call-minutes/month, an operating cost of $.05 per call-minute, and a maintenance cost of 1%, as previously mentioned. The user cost discussed in the above paragraphs does not include the cost of the mobile equipment. The cost of the terminal for the UHF baseline system is assumed to be $2300. Of the $2300, $800 is the cost of the antenna, which has been assumed to be a mechanically steerable, 1 X 4 tilted array having a gain of 10 dBi. The three L-band configurations considered require three different types of terminals, each having a different antenna gain. Assuming all terminals utilize the same type of mechanical antenna, the cost of the L-band terminals is not expected to be significantly different from the cost of the UHF terminal.

As indicated in Figure 7-1, the monthly cost of the mobile terminal increases at a rate of approximately $19 for each $1000 increase in the terminal cost. A small increase or decrease of $100 to $200 in the terminal cost will not significantly change the monthly cost. Consequently, the mobile equipment cost for the three L-band configurations is assumed to be the same as that of the UHF baseline, or roughly $45 per month. The total user cost is thus, $80, $65, and $60 for the 10-dBi, 13-dBi, and 16-dBi configurations.

The mobile terminal cost and the total monthly cost are included in Table 5-4.

5.6 A COMPARISON OF THE THREE L-BAND CONFIGURATIONS

The satellite capacity varies from 1900 to 7400 channels per satellite, and the total user cost from $60 to $80 per month for the three L-band configurations. The design of the satellite is identical for all three configurations. The only differences between these configurations are the cost of the ground segment and the gain of the mobile antenna. The difference in the cost of the ground segment is small, and it does not affect the user cost significantly. The major contributor to the difference is the mobile antenna. Based on Table 5-4, it appears that the 16-dBi mobile antenna is the best choice among the three. There is, however, a major problem associated with the 16-dBi antenna.

Based on work performed by MSAT-X, the 10-dBi, 4-element tilted linear array, operating at UHF, has a height of about 7 inches and a diameter of about 36 inches. This probably is the upper limit of antenna size that can be implemented on the top of a vehicle.

A 16-dBi mechanical antenna operating at L-band can stay within the above dimensions by using a 2 X 8 planar array. The 2 X 8 array, however, would have a narrower elevation pattern than the 1 X 4 linear array, which is designed to provide an adequate coverage for elevation angles ranging from 20 to 60 degrees. To get the needed elevation coverage, tracking in the elevation direction may be required, or a manual switch may be necessary. This switch would allow the user to manually switch the antenna orientation in the elevation direction as the vehicle travels from one geographical area to another. Both of these requirements would either complicate the design of the antenna, or result in operational constraints. The 16-dBi antenna is, therefore, not a likely choice.

The configuration using a 13-dBi antenna provides a satellite capacity and a user cost that are both comparable to those of the UHF baseline. This antenna has a lower profile and a smaller diameter than the 2 X 8 array, and, hence, can to be easily implemented on the top of a vehicle. Furthermore, it does not have the elevation coverage problem of the 2 X 8 array. Based on these arguments, the 13-dBi configuration is considered as the likely candidate for the L-band design.

5.7 A COMPARISON OF THE UHF AND L-BAND SYSTEMS

Both the UHF and L-band have been considered by some as a possible operating frequency for a mobile satellite system. Ultimately, the UHF-versus-L-band issue will be decided by what the FCC will do. Aside from the FCC action, is one band favored over the other? To answer this question, a comparison of the baseline UHF system and the 13-dBi L-band system will be performed. (It is noted that there are also some who have considered a hybrid system, using both L-band and UHF. A hybrid system would alleviate the spectrum congestion. Such a system is not considered in this study.)

In terms of the system capacity, system cost, and the user monthly cost, the 13-dBi L-band system, is about the same as the UHF system. There are no noticeable advantages, nor disadvantages. The comparison will therefore focus on the mobile antenna and the satellite.

5.7.1 Mobile Antenna

The mechanically steerable, nonconformal linear array will serve as the basis of the comparison. There are other types of antennas being investigated for possible application to the mobile satellite system, such as an electronic phase array. This type of antenna, however, is believed to be too costly for the second-generation system. (Please refer to Appendix B for more information on the mobile antenna, and Chapter 6 for the estimated mobile terminal cost.)

Although the gain of the L-band mobile antenna is 3 dB higher than its UHF counterpart, its physical size is actually smaller than the UHF antenna, due to the increase in frequency. As previously mentioned, the UHF antenna,

which is a 1 X 4 linear array, is estimated to have a diameter of 36 inches and a height of 7 inches. With a 1 X 8 linear array, a gain of 13 dB can be obtained. At L-band, this array would have the same diameter as the UHF antenna, 36 inches, and a height of 3-1/2 inches, which is half of the height of the UHF antenna. The low profile is the biggest advantage of the L-band antenna.

One possible disadvantage of a 13-dBi L-band antenna is its relatively narrow azimuthal beamwidth, which may place a more stringent requirement on its tracking system.

Other properties of the L-band antenna, such as the elevation coverage and cost, are believed to be similar to the UHF antenna.

5.7.2 The Satellites

The L-band satellite, which has a 10-m antenna, has several advantages over the 20-m UHF satellite. Although studies performed by two contractors [1, 2] have indicated the feasibility of flying a 20-m antenna on the baseline satellite bus, there are several challenges posed by the 20-m deployable antenna, which must be overcome through further research and development. The challenges are in the area of spacecraft packaging, the attitude and orbit control, the perigee kick motor, and the potential inteference due to passive intermod (PIM). While these challenges are believed to be within the technical capability of the 1990's, and are judged to be manageable with further studies, there is a certain degree of risk associated with the 20-m satellite. The risk could delay the implementation of the system. The successful deployment of the UHF system, therefore, requires further development efforts. The

L-band satellite, on the other hand, eliminates most of the challenges facing the UHF satellite, and the amount of risk involved is minimal. Its implementation does not require as much future effort as the UHF system.

REFERENCES

[1] Mobile Satellite Configuration Study, Final Oral Report, RCA Astro Electronics, January 23, 1985

[2] Spacecraft Configuration Study for the Second Generation Mobile Satellite System, Final Report, Ford Aerospace and Communications Corp., January 1985.

CHAPTER 6

EFFECTS OF THE MOBILE ANTENNA DESIGN, AVAILABLE FREQUENCY BAND, CHANNEL SPACING, AND REQUIRED EB/NO ON THE CAPACITY OF THE MOBILE SATELLITE SYSTEM AND THE USER COST

6.1 INTRODUCTION

The design of the baseline system, presented in Chapters 2 and 3, is based on a set of study assumptions or requirements, including the design of the mobile antenna, the allocated bandwidth, the modulation/demodulation scheme, and the projected user demand. While these assumptions are intended to be practical, some may be arbitrary, and many may have been established based on insufficient information. As a result, these assumptions may deviate from reality.

The design of the satellite system, to a great extent, is insensitive to, or, independent of, some of the assumptions, such as the modulation/demodulation method. On the other hand, some of study assumptions, such as the assumed bandwidth allocation, may significantly alter the design of the satellite.

The purpose of this chapter is to examine the impacts on the design of the system, particularly in the areas of the system capacity and the user cost, due to a change in the following assumptions:

- o Mobile antenna: LGA instead of MGA
- o Allocated bandwidth: 4 MHz instead of 10 MHz
- o Channel spacing and required EB/NO

To facilitate the analysis of the sensitivity of the user cost to the study assumptions, a parametric study of the user cost is presented in Section 7.2, using the cost model in Appendix C. For convenience, all discussions on monthly usage and charge rates are based on one-way communications as previously mentioned.

6.2 USER COST ANALYSIS

The cost that must be borne by the system users is composed of the cost of the mobile terminal and the cost of the mobile satellite system. For the sake of convenience, the cost of the mobile satellite system, or simply the system cost, is defined to consist of the cost of the space segment, the ground segment, and all other necessary costs, including the operation and maintenance of the system, insurance, and investment return. The cost of the space segment consists of the cost of the satellites, launch service, and incentives for the satellite manufacturers. The cost of the ground segment covers the Network Management Center, gateway stations, and base stations. The sensitivity of the user cost to the cost of the mobile terminal and the cost of the system is discussed in the following sections.

6.2.1 Sensitivity to the Cost of the Mobile Terminal

The cost of the mobile terminal is the purchase price of the equipment, plus an installation charge, if any. The mobile terminal cost can be either a lump-sum payment, or a monthly installment. The latter can be interpreted as a monthly lease fee for a user choosing to lease instead of buying the equipment. The monthly cost, or monthly payment has been estimated using a rate of return of 12% above the inflation rate (Figure 6-1). As indicated in the figure, the monthly payment is a linear function of the cost of the mobile terminal. Every $1000 of mobile equipment corresponds to a monthly payment of approximately $19.40. All dollars refer to 1985 dollars. The estimated monthly cost is based on an equipment lifetime of 15 years.

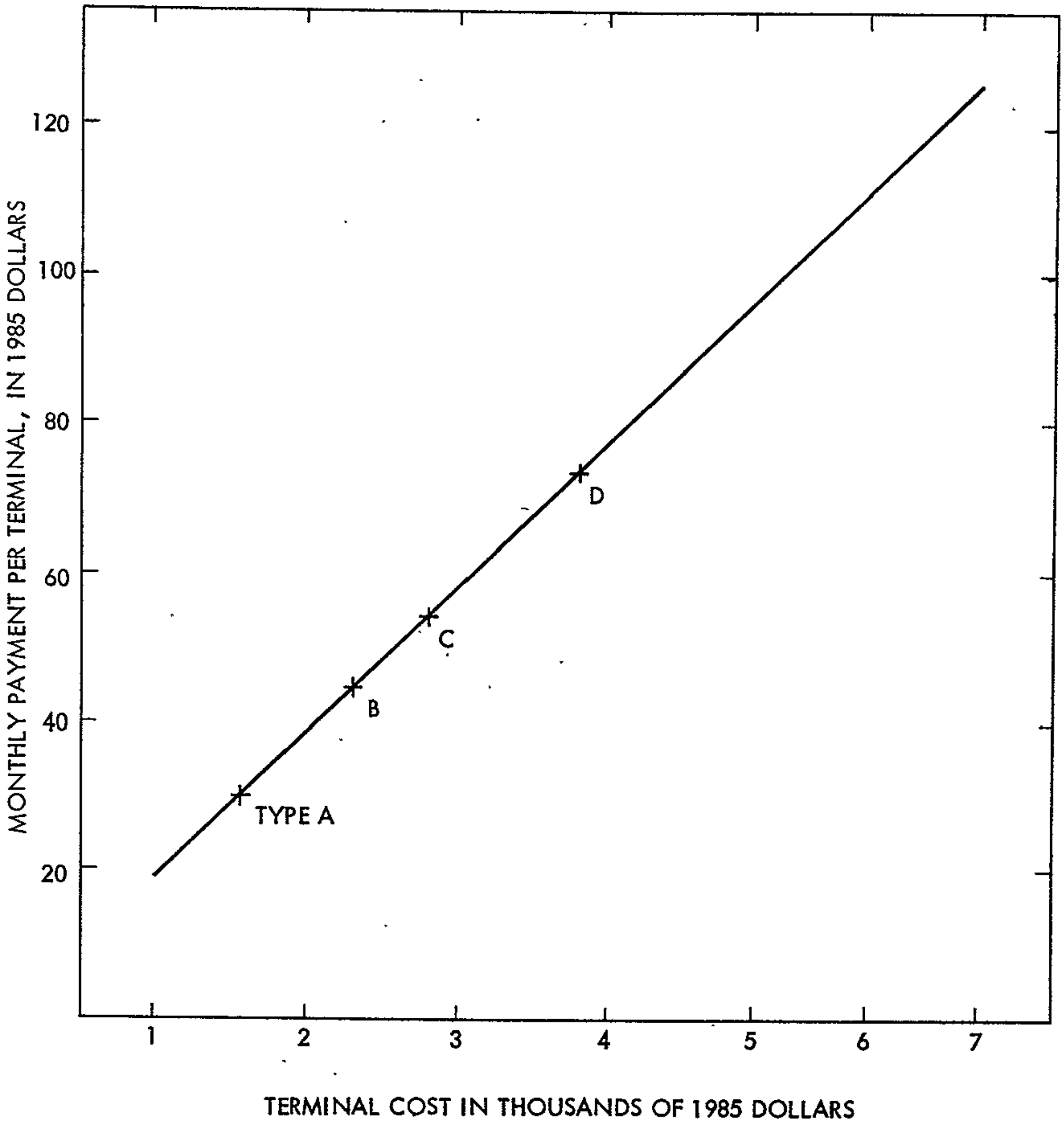


Figure 6-1. Mobile Terminal Cost Versus Monthly Payment

The cost of the mobile terminal, shown in the figure, ranges from about $1000 to $7000. The low end represents the cost of the most inexpensive terminal using an LGA. The mobile antenna assumed in the baseline design is an MGA. The cost of an MGA terminal is estimated to vary from about $2300 to $3800, depending on the specific type of MGA employed. For the purpose of comparison, the estimated cost of various mobile terminals is summarized in Table 6-1. The cost data is partly based on the work of MSAT-X. It should be noted that these estimates are preliminary and are subject to future modifications. The various types of terminals are designated in Table 6-1 as type A, B, C, and D. Type B is the lowest cost MGA terminal and is the baseline terminal.

The monthly cost for various types of terminals is shown in Figure 6-1 and Table 6-1. The difference between the LGA terminal and the baseline terminal is about $15 per month, which is relatively insignificant, compared to the advantages offered by an MGA. The difference between a baseline MGA terminal and the most expensive MGA terminal is about $30.

6.2.2 Sensitivity to the Cost of the System

The user cost, in reality, will probably consist of a usage charge and a fixed monthly charge, as previously mentioned. To analyze the sensitivity of both the usage charge and the monthly charge separately would be complicated, due to their interrelationship and the dependence on the number of users. For the sensitivity analysis, it is sufficient to examine the total user cost based on a fixed amount of usage and assuming no monthly service charge.

Table 6-1.

Estimated Mobile Terminal Cost

in 1985 Dollars

Types of Terminals	Cost of the Transceiver $	Cost of[1] the Antenna $	Total Terminal Cost $	Estimated[2] Monthly Cost $	Type of Mobile Antenna
A	1500	50	1550	30	LGA
B	1500	800	2300	45	MGA, 1 X 4 tilted, mechanically steerable array.
C	1500	1300	2800	54	MGA, mechanically steerable conformal array.
D	1500	2300	3800	74	MGA, electronically scanned conformal array.

NOTES

(1) Estimated consumer cost.
(2) Based on an equipment lifetime of 15 years.

The user monthly cost, excluding the cost of the mobile equipment, is shown in Figure 6-2 as a function of the system capacity. The estimated user cost is based on a usage of 100 call-minutes per month, and a rate of return of 12% above the inflation rate. The cost of ground and space segments is shown in the figure as a parameter. The total system cost includes, in addition to the cost of the space and the ground segments, the cost of insurance, operation, maintenance, etc., as previously mentioned. In estimating the user cost, the operating cost has been assumed to be \$0.05 per call-minute, and maintenance has been 1% of the replacement cost of the system. These assumptions have been and will be applied to all cost estimates throughout the entire report, unless explicitly stated otherwise.

For convenience, Figure 6-2 has been rearranged and shown in Figure 6-3 with the system capacity as a parameter. The system capacity shown in both Figures 6-2 and 6-3 is the equivalent number of the revenue-generating channels at saturation. The revenue-generating channels are those that generate revenue continuously. Because of the diurnal variation and the skewed user population, the number of revenue-generating channels is assumed to be 1/4 of the actual satellite channels.

Figures 6-2 and 6-3 give the sensitivity of the user cost to the combined cost of the space and ground segments. These figures can also be used to analyze the effects of the space segment cost for a given ground segment cost, and vice versa.

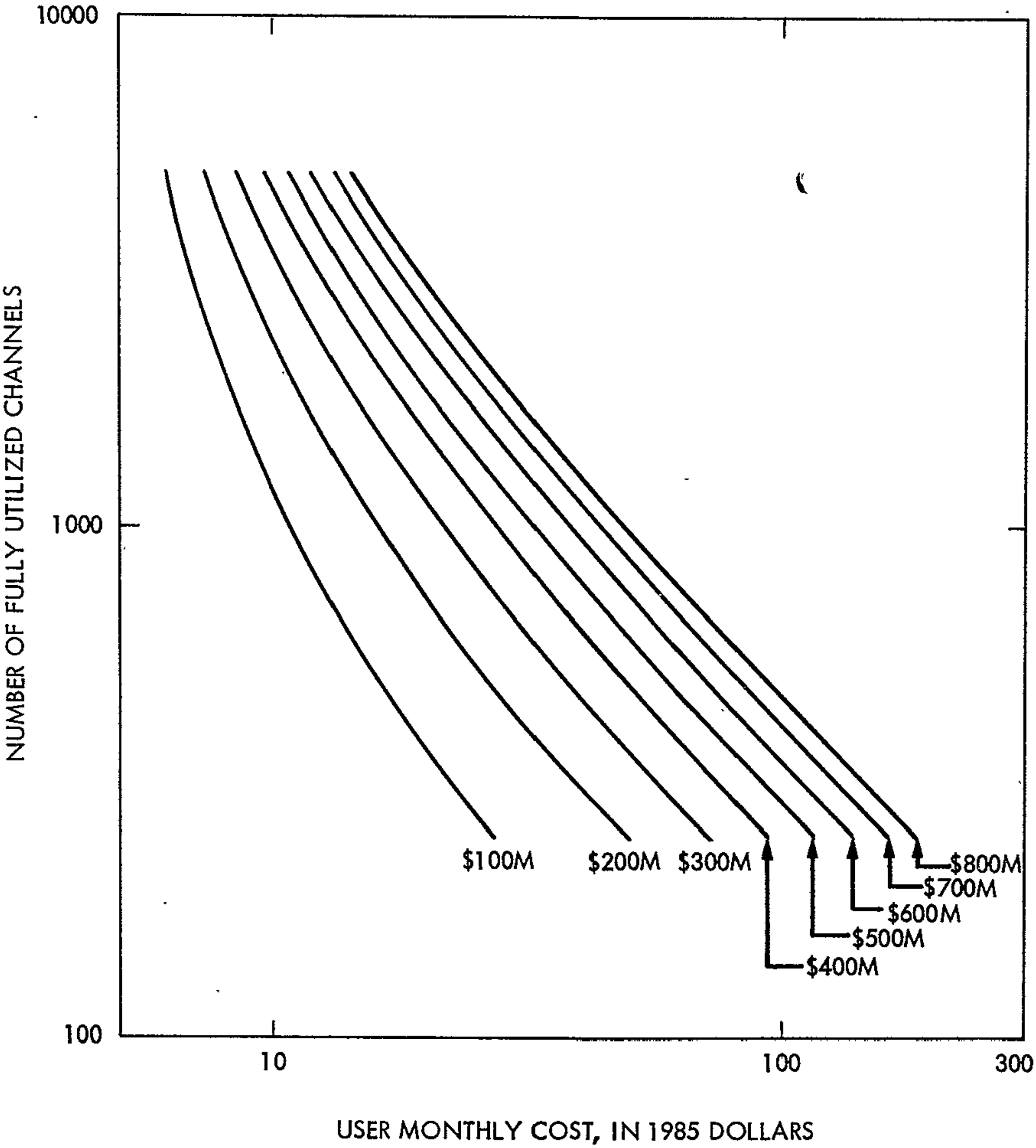


Figure 6-2. Sensitivity of User Cost to the System Capacity With the Cost of the Space and Ground Segments as a Parameter (Based on 100 Call-Minutes Per Month)

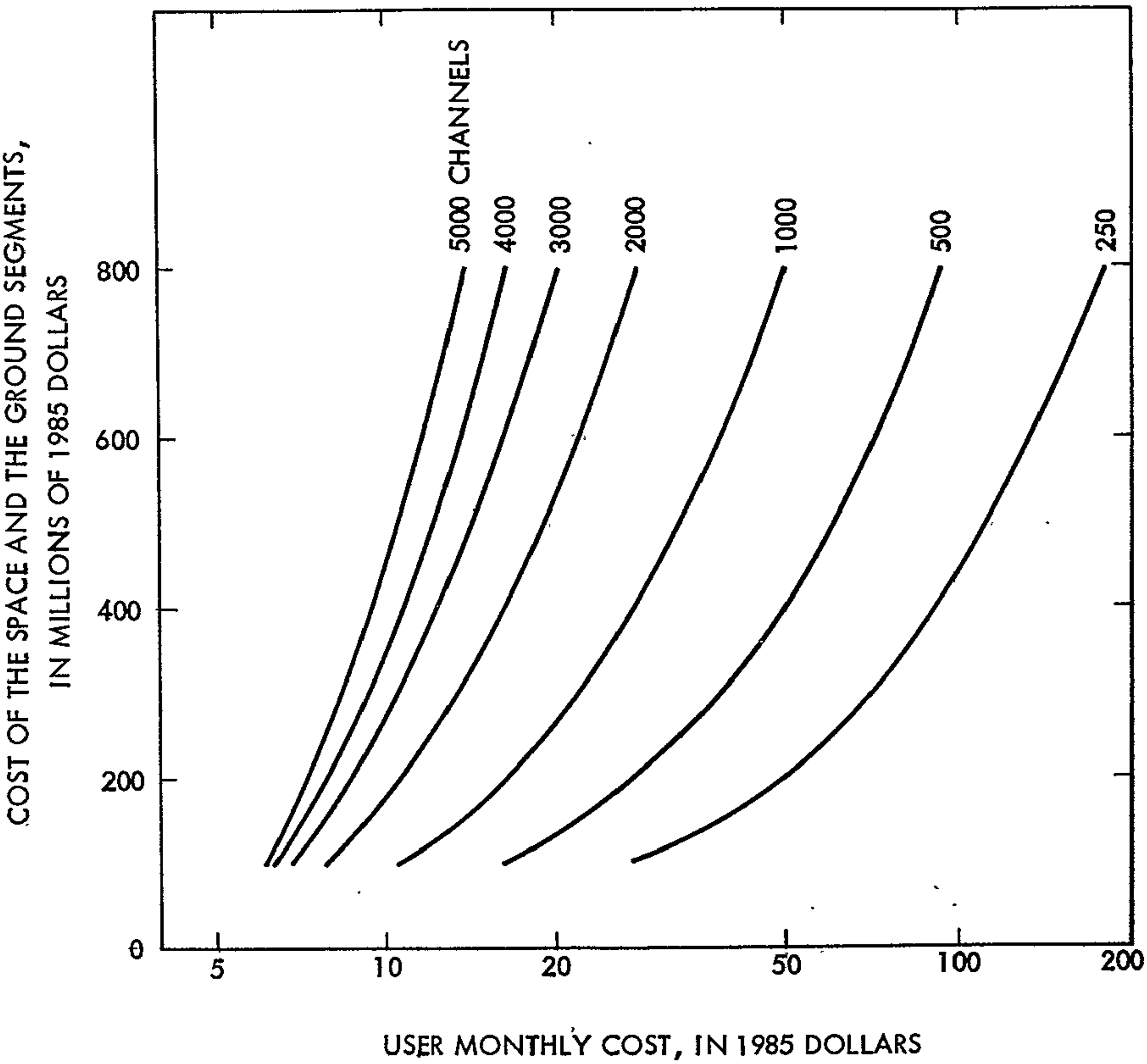


Figure 6-3. Sensitivity of User Monthly Cost to the System Cost With the Number of Filled Channels as a Parameter (Based on 100 Call-Minutes Per Month)

6.3 EFFECTS OF USING A LOW-GAIN MOBILE ANTENNA

The baseline system is designed to operate with an MGA on the mobile terminal, which has a gain of 10 dBi. Because the MGA is more costly than the LGA, there has been some speculation that an LGA may make the mobile satellite system more attractive to the general public. With a 10-MHz allocation, the satellites designed for the MGA can operate in either the LGA or the MGA environment without modifications. However, with the LGA terminals, the system capacity and user cost will be significantly different from those using the MGA terminals.

6.3.1 System Capacity and User Cost

The number of satellite channels for the UHF baseline system is 4076 and 4612 for the east and west satellites, respectively. With the mobile antenna gain reduced by a factor of 4, or 6 dB, the resulting satellite channels would be 1019 and 1153 for the east and west satellites, respectively, giving a total of 2172 channels. Allowing a factor of 2 to account for the skewed user density, the effective number of channels would be 1086.

It is estimated that about 180,000 users would be supported, assuming a voice-to-data user ratio of 0.2. Compared to the baseline system, this represents a reduction in the number of users by a factor of almost 5. To maintain the same capacity as the UHF baseline system, it would require a class of satellite much more powerful and heavier than the baseline satellite.

In addition to a lower capacity, the use of an LGA would increase the user cost. Although the cost of an LGA is much lower than an MGA, the user monthly cost would be higher because of the reduced capacity. Assuming a usage of 100 minutes, the user cost has been estimated to be $65 for the baseline system using the least expensive MGA terminals (Chapter 3). For the same amount of usage and the same satellites, the user monthly cost for the LGA system would be $90 based on Figures 6-1 and 6-2, and Table 6-1. This is about 40% higher than the baseline system. The corresponding per minute charge is estimated to be $0.60, or a factor of 3 higher than that of the baseline system, which is estimated to be $0.20 per call-minute in the absence of a MSC. The use of an LGA in place of an MGA would have a serious impact on the financial soundness of the system.

6.3.2 Impacts on the Spectrum Requirement

Along with the reduction of system capacity, the LGA would ease the requirement for spectrum. As previously mentioned, the satellite channels would be 1019 and 1153 with an LGA. The total bandwidth required would be approximately 5 MHz per satellite assuming a 5-kHz channel spacing. With a frequency reuse factor of 7, the bandwidth requirement would be reduced to about 1.5 MHz. A 10-MHz allocation could therefore support two satellites with no frequency reuse, and more with frequency reuse.

6.4 IMPACTS OF A 4-MHz ALLOCATION

The present design requires an allocation of 10 MHz. There has been some speculation that a 4-MHz band pair may be allocated, instead of a 10-MHz pair. Reducing the available bandwidth from 10 MHz to 4 MHz would seriously degrade the system capacity.

With a 7-frequency reuse, the 20-m satellite system provides a total of 8688 channels for a 10-MHz bandwidth. Using the same frequency reuse, the number of channels that can be supported by the 4-MHz band is only 5142 channels. Thus, the capacity of the system using 4-MHz band will be severely limited by frequency. In order to increase the capacity, the available frequency band must be reused as much as possible. However, there is an upper limit of the reuse of the frequency due to interbeam interference. Table 6-2 tabulates the total number of channels supported by a 4-MHz bandwidth for different reuse factors. Also tabulated in the table is the estimated interbeam isolation based on the 20-m, single-element feed design. It is noted that an overlapping feed design would result in a communications payload that is too heavy for the baseline satellite bus, as indicated in Chapter 2.

Based on Table 6-2, a frequency reuse factor of 4 would offer enough channels. However, the corresponding interbeam isolation, which is estimated to be 12 dB, would result in an overall C/I of 5.7 and 11.4 dB for the mobile-to-mobile and fixed-station-to-mobile communications, respectively (Table 2-10). An overall C/I of less than 10 to 12 dB would severely degrade the link performance. To maintain an acceptable overall C/I, the frequency reuse factor probably cannot be less than 6, corresponding to an interbeam isolation of approximately 17 dB.

Assuming a frequency reuse factor of 6, a 4-MHz band can support 6000 channels, or approximately 570,000 users, based on a voice-to-data user ratio of 0.2. The resulting user cost, excluding the cost of the mobile terminal, is estimated to be $25 for 100 call-minutes, or $0.25 per minute. Compared to the charge rate for the baseline system with a 10 MHz allocation, this represents an increase of about 25%. The loss of 6 MHz of bandwidth would cost the users a total of $40M annually, or $7M per MHz.

Table 6-2. The Number of Channels Supported by a 4-MHz Bandwidth (Frequency Limited Case)

Frequency Reuse Factor	Number of Channels East Sat.	West Sat.	Total	Interbeam Isolation, dB(1)
7	2742	2400	5142	20
6	3200	2800	6000	17
5	3840	3360	7200	14
4	4800	4200	9000	12

NOTE:

(1) Based on the 20-m, single-element design.

6.5 EFFECTS OF CHANNEL SPACING AND REQUIRED EB/NO

The design of the satellite is basically transparent to the type of modulation/demodulation scheme being employed. The system capacity, however, depends, to a certain extent, on the performance of the modulator/demodulator, in terms of the necessary channel bandwidth and the EB/NO required to meet a specified bit-error performance. The baseline modulation scheme is GMSK, with an assumed channel spacing of 5 kHz. The baseline demodulation has been assumed to meet a bit-error performance of 10^{-3} at an EB/NO of 10.7 dB. The impact of a larger channel bandwidth and a higher required EB/NO will be examined in the following sections.

6.5.1 Channel Spacing

With a 7-frequency reuse and a 10-MHz bandwidth, the capacity of the baseline system is limited by the spacecraft power, not the available frequency band. The number of channels that can be supported by the 10-MHz band is 6857 and 6000 for the east and west satellites, respectively, giving a total of 12,857 channels. The channels that can be powered up by the baseline spacecraft is 4076 for the east satellite, and 4612 for the west satellite, or a total of 8688 channels.

The channel spacing is assumed to be 5 kHz in the baseline design. If the channel spacing is increased to 6 kHz, the total number of channels supported by the 10-MHz band would be reduced by a factor of 5/6, or by 5714 channels for the east satellite, and 5000 for the west satellite.

Compared to the number of channels that the satellites have power for, it is clear that the capacity of the system is still limited by power.

However, if the channel spacing is further increased to 7 kHz, the system would then become frequency limited. At 7 kHz per channel, a 10-MHz band can provide 4897 channels for the east satellite, and 4285 channels for the west satellite. The number of channels available to the west satellite is therefore 327 channels less than what it has power for. The west satellite thus becomes frequency limited. The lost capacity translates directly into a loss in revenue.

The number of channels as determined by the spacecraft power and by the available frequency band is shown in Table 6-3 for selected channel spacings. The number of channels lost and the amount of revenue reduction, relative to the baseline system, are also tabulated in Table 6-3. Based on a charge rate of $0.20 per call-minute, the loss of revenue is about $26K per channel-year. (The lost revenue, minus its associated operating cost, can be viewed as an additional cost to the user.) The amount of lost revenue is equal to 1/4 of the product of the charge rate, the number of lost channels, and the number of minutes per year. The factor 1/4 accounts for the diurnal variation and the skewed user population.

6.5.2 Required EB/NO

The baseline design requires an EB/NO of 10.7 dB. If the required EB/NO is increased, the system capacity would be proportionally reduced, and the user cost would be increased accordingly. Table 6-4 tabulates the system capacity as a function of the required EB/NO. The amount of lost revenue, and the amount of additional cost that the users would have to share, are also included.

Table 6-3. Effects of a Larger Channel Spacing

	Number of Satellite Channels			Number[1] of Lost Channels	Amount[1] of Lost Revenue $M
	East Satellite	West Satellite	Total		
Power-Limited Case (Baseline Design)	4076	4612	8688	0	0
Frequency-Limited Cases					
a. 5-kHz Channels	6857	6000	12857	0	0
b. 6-kHz Channels	5714	5000	10714	0	0
c. 7-kHz Channels	4897	4285[2]	9183	327	9
d. 8-kHz Channels	4285	3750	8035	862	23
e. 9-kHz Channels	3809[3]	3333	7142	1546	41
f. 10-kHz Channels	3428	3000	6428	2260	59

Notes:

(1) Relative to the baseline system.
(2) The west satellite becomes frequency-limited at a channel spacing of 7 kHz.
(3) The east satellite becomes frequency-limited at a channel spacing of 9 kHz.

Table 6-4. Effects of a Higher Required EB/NO

Required EB/NO, dB	Number of Satellite Channels	Number of Lost Channels	Amount of Lost Revenue, $M	Estimated Charge Rate $/min(1)	Additional Annual User Cost Year(2) $M/Year	Comments
10.7	8688	0	0	0.20	0	Baseline Design
11.7	6901	1786	47	0.25	35	
12.7	5481	3206	84	0.30	60	
13.7	4354	4333	114	0.35	80	
14.7	3458	5229	137	0.40	100	
15.7	2747	5940	156	0.50	115	
16.7	2182	6505	171	0.60	120	

Notes:

(1) Assume no monthly service charge (MSC).

(2) Total additional cost for all users after saturation.

The additional cost and the amount of capacity reduction, presented in both Tables 6-3 and 6-4, are referenced to the baseline system. Roughly, the cost for a 1-dB increase in the required EB/NO ranges from $15M to $50M per year for the range of EB/NO considered.

6.6 DISCUSSION

The cost tradeoff of the LGA terminals versus the MGA terminals presented in Section 6.3 concluded that the MGA, although more costly than the LGA, would result in a lower user monthly cost. This conclusion was based on a number of assumptions regarding the costs of LGA terminals, the MGA terminals, and the amount of usage. Specifically, the cost of an MGA terminal was assumed to be $2300, of which the antenna accounted for $800 and the transceiver $1500. The cost of the LGA terminal was $1550, which included the cost of the LGA ($50) and the cost of the transceiver ($1500). Since both the transceiver and the antenna are in the development stage, the actual costs may deviate from those assumed in Section 6.3. A more expensive MGA or transceiver or a much lower monthly usage may alter the above conclusion.

Figure 6-4 shows the threshold MGA cost (not including the cost of the transceiver) as a function of the amount of usage. The threshold MGA cost is the cost at which the user monthly cost for a system using MGA terminals is equal to that using LGA terminals. As indicated in the figure, the threshold MGA cost is a linear function of the amount of usage, i.e., the number of call-minutes. For a user having 100 call-minutes per month, the break point for the MGA cost is approximately $2100. If the actual cost of the MGA exceeds $2100, the cost

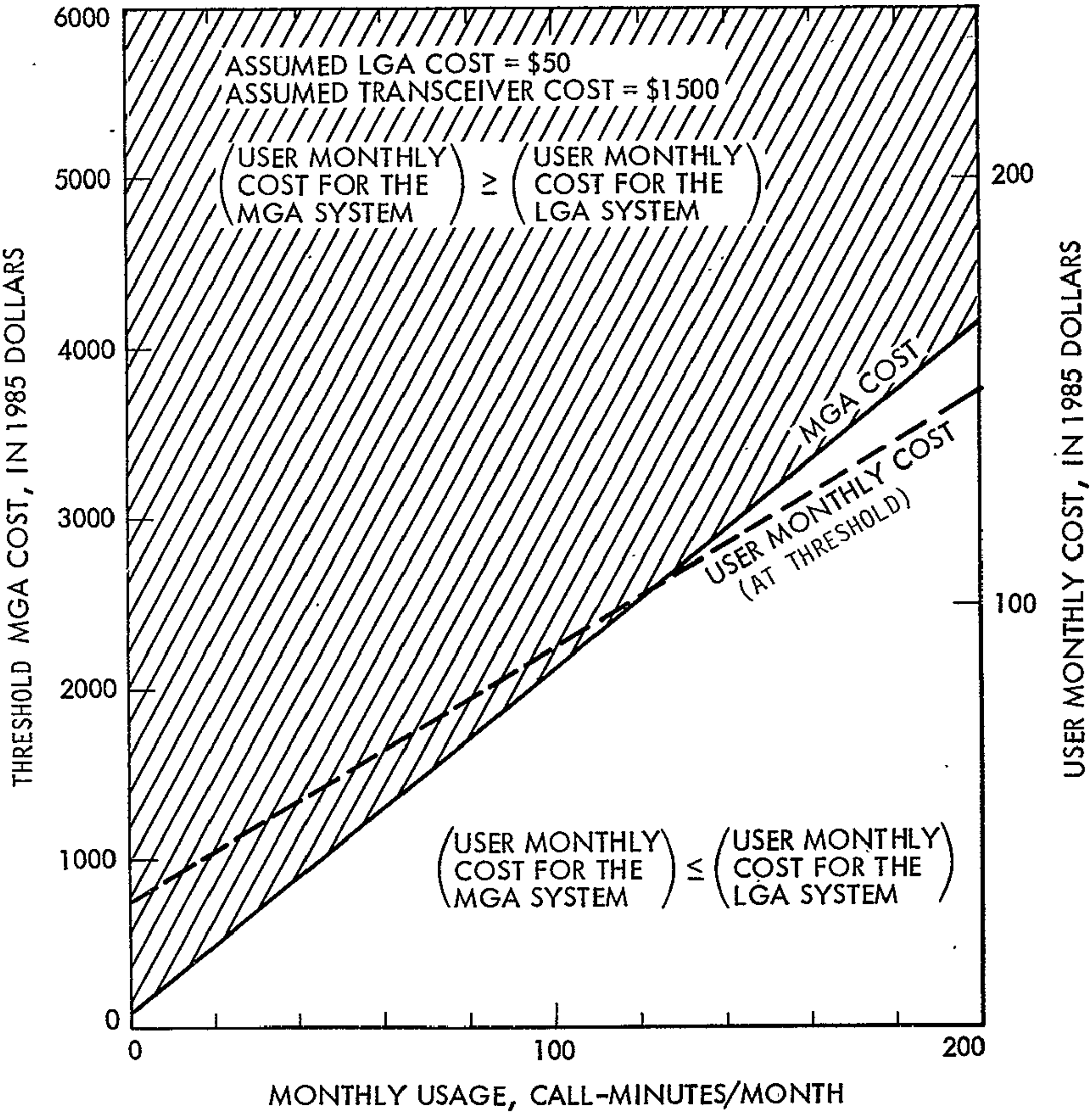


Figure 6-4. Threshold MGA Cost Versus Monthly Usage (The Threshold MGA Cost is the Cost That Results in a User Monthly Cost Equal to That of a System Using LGA Terminals)

tradeoff would favor the LGA terminals instead of the MGA terminals. For an amount of 40 call-minutes per month, the MGA cost would have to be less than $900 in order to have a lower user monthly cost than the LGA. The estimated cost for the baseline antenna (which is a mechanical 1 X 4 tilted array) is $800. One would favor this antenna over the LGA if the monthly usage exceeds 40 call-minutes. On the other hand, the electronic phased array, which is estimated to cost $2300, would have an advantage over the LGA only if the amount of usage is more than 110 minutes.

The above discussion has been solely based upon the user monthly cost. The willingness and readiness of the customers to pay for the necessary monthly charges have not been considered. The monthly user cost is included in Figure 6-4 for reference.

Implicity in Figure 6-4 is the assumed costs of the LGA and the transceiver, which have been fixed at $50 and $1500 respectively. In theory, the maximum MGA cost is a function of the transceiver cost. For a transceiver costing $1000 to $2000, the effect is negligible, as indicated in Figure 6-5. The transceiver cost is the cost of the mobile terminal less the cost of the antenna. The transceiver has been assumed to be the same for both the LGA and MGA terminals.

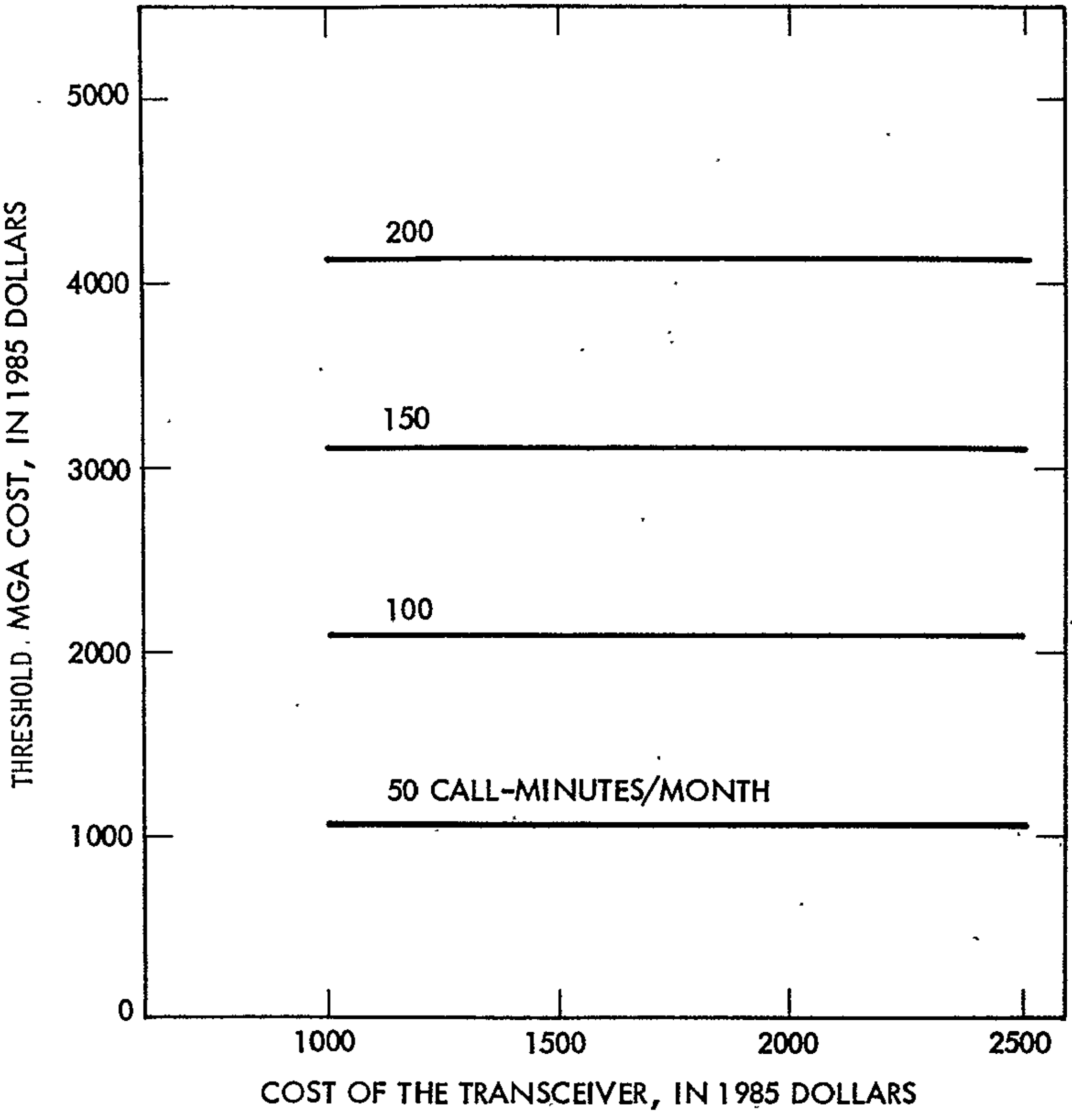


Figure 6-5. Threshold MGA Cost Versus the Cost of the Transceiver (the Threshold MGA Cost is the Cost That Yields a User Monthly Cost Equal to That of a LGA System)

Chapter 7

AREAS OF FURTHER STUDY

7.0 INTRODUCTION

Studies [1 and 2] have indicated the feasibility of implementing a 20-m mobile satellite using a commercial communications satellite bus that is currently being developed or is already in existence. There are, however, challenges, problems, uncertainties, and, hence, risks posed by the 20-m satellite. While it is believed that the technical challenges are within the capability of the 1990 technology, that the problems are manageable, and that the risks and uncertainties can be minimized, further studies are necessary to ensure the implementation of the system in a timely and cost-effective manner. With this in mind, the areas of further necessary study will be identified.

The areas of further study fall in two categories. The first category involves studies of critical importance to MSAT-2. These studies are in the area of the attitude control and antenna structural analysis. The second category of studies, while not as important as the first category, are recommended to enhance the system and lower the cost.

7.1 ATTITUDE CONTROL AND ANTENNA STRUCTURAL CHARACTERISTICS

Perhaps the most challenging technology in implementing the 20-m satellite is the ability of the attitude and orbit control subsystem to adequately maintain the orientation of the spacecraft and to point the large reflector with a prescribed accuracy. Although preliminary assessments indicate that existing control subsystems on the high-power communications satellites considered in this study would be capable of meeting this challenge, further research is necessary.

In order to properly design the control subsystem, it is necessary to determine the structural characteristics of the antenna, including the reflector and its masts. Such data can be obtained by a thorough computer modeling or by direct measurements. Due to the limited scope of this study, neither of these has been performed. The requirements of the attitude and orbit control subsystem have been assessed using simplistic estimates of the structural property of the antenna. Consequently, there is a degree of uncertainty as to whether the existing control subsystem design could be employed without modifications. An in-depth structural analysis and a complete assessment of the attitude control requirements are therefore needed to eliminate or reduce the uncertainty and to determine if modification, or even a new design, will be necessary.

It should be noted that such a study would be necessary even with a 15-m antenna. The requirements for the attitude control subsystem for a 15-m antenna, of course, would be less stringent than those for a 20-m antenna.

7.2 OPTIMIZED ANTENNA BOOM DESIGN AND EFFICIENT SPACECRAFT PACKAGING

The antenna-supporting structure and its deployment mechanism have a significant impact on the stowed length and weight of the spacecraft and the structure of the antenna, and, hence, on the requirements for the attitude control subsystem. The antenna boom designs used here have not been optimized, thus resulting in a large stowed length. An optimized design could potentially result in a more compact configuration, reducing the spacecraft's weight or increasing its power. As shown in Chapter 3, the launch cost for a 20-m UHF satellite is approximately $55M based on the stowed length of the spacecraft. If the stowed length were reduced and the launch cost based on the cargo weight of the spacecraft, the cost would be $35M to $40M, saving $15M to $20M per satellite. For three satellites, the

savings could be substantial. In order to realize some or all of these savings, alternative methods of packaging the spacecraft and different design concepts for the boom and the deployment mechanism should therefore be investigated.

7.3 OPERATING MSAT-2 IN THE PRESENCE OF MGA AND LGA TERMINALS

MSAT-2 has been designed for mobile terminals equipped with an MGA. The addition of other types of terminals, the LGA terminals in particular, would create a compatibility problem, although substituting LGA terminals for MGA terminals would not. The only effects of such a substitution would be a reduction in capacity, higher per-minute charges, and the absence of orbit reuse (10-MHz allocation).

The presence of both MGA and LGA terminals, however, creates two problems. First, LGA terminals would not be able to discriminate between adjacent satellites, hence, making orbit reuse difficult. Secondly, the LGA terminals would, for a given link performance, require a higher spacecraft EIRP than the MGA terminals, which in turn would create a design problem. The lack of the LGA's discrimination could be circumvented by assigning a portion of the channels in each beam or subband to LGA operations exclusively (Fig. 7-1). For a given subband, the portion that is assigned to the LGA in one satellite would be left vacant in the other satellite in order to avoid intersatellite interference. Consequently, the efficiency of spectrum utilization would be greatly reduced.

However, the difference in the EIRP requirement between the LGA and MGA users would mean either a more complicated and heavier transponder or a much worse intermod interference for the MGA users, both of which would drastically reduce the satellite's capacity. One possible way to avoid these problems is to restrict the LGA users to a much lower data rate. A more detailed study is required.

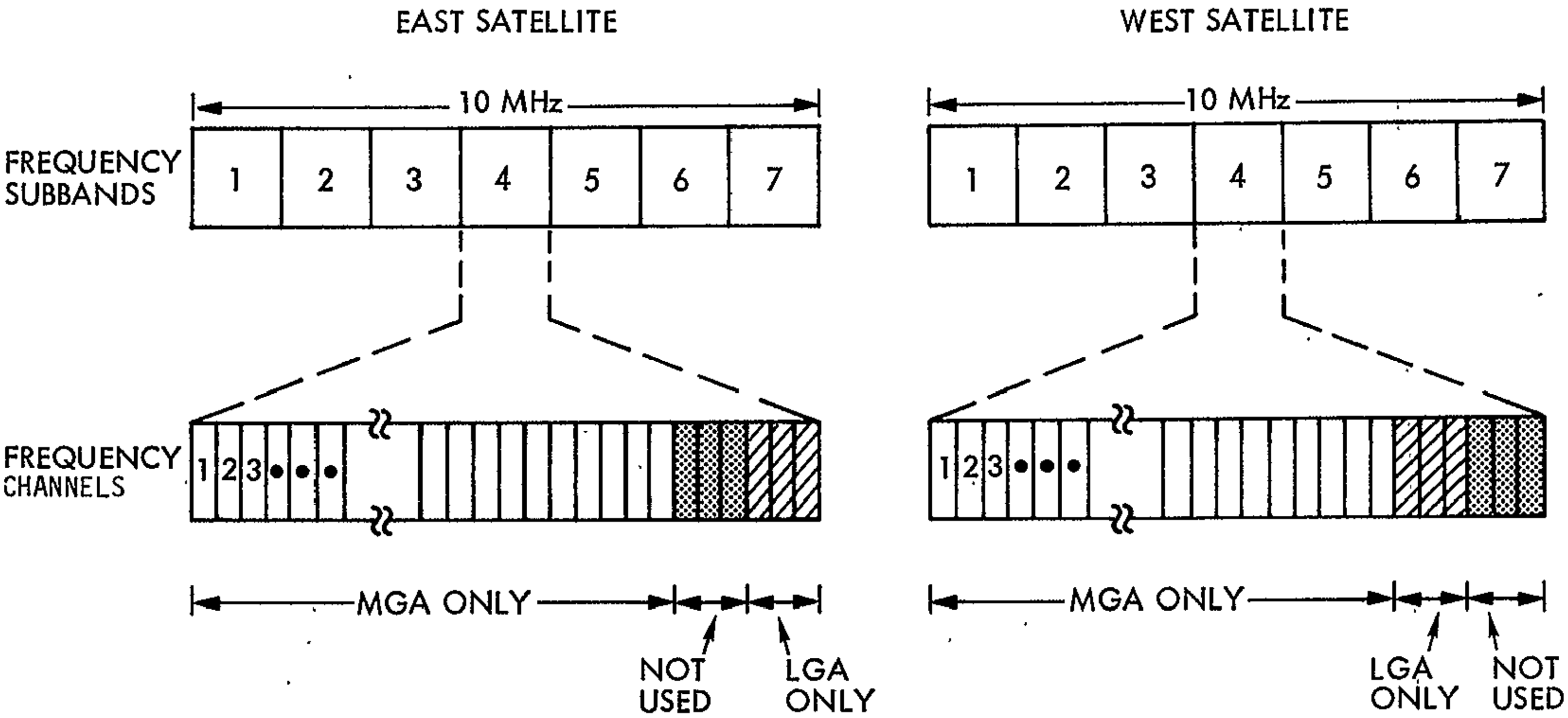


Figure 7-1. A Frequency Plan for MGA/LGA Operations

7.4 OTHER AREAS OF IMPROVEMENT

In addition to the above technology improvements, there are a few areas which can potentially enhance the system in terms of an increase in capacity or a decrease in user cost. One area is the power amplifiers of the transponder. In the baseline design, the linearized efficiency of the transponder, i.e., the HPA's, has been assumed to be 26%, which is substantially lower than the advertised efficiency of some linearized power amplifiers. Studies should therefore be performed to improve the power amplifier efficiency, or to investigate the applicability of various types of highly efficient linearized amplifiers.

Another area of interest is to investigate possible methods of dealing with the skewed user population. As previously indicated, the skewed user population lowers the effective capacity of a system designed for a uniform user density. One way to handle the skewed population is to vary the size of each beam according to the number of the projected users in that beam such that the number of users and, hence, the number of channels per beam are uniform for all beams. Another possible solution is to size the power amplifier in each beam according to the number of projected users in that beam. Neither method has been explored in this study and a capacity reduction factor of 1/2 has been allowed to account for the effects of the skewed user population. In view of the potential gain, further study is warranted.

The potential to further enhance the system by employing on-board switching and on-board signal processing should also be examined for future mobile satellite systems. The transponded uplink interference accounts for a significant portion of the total end-to-end interference in the present design. With an on-board signal processing, the uplink interference and uplink multipath fading can be decoupled from the down-link, resulting in a better performance. Partial on-board switching can eliminate the double hops presently required for mobile-to-mobile communications. Although these technologies are not mandatory for MSAT-2, their potential should not be ignored.

REFERENCES

[1] Spacecraft Configuration Study for the Second Generation Mobile Satellite System, Final Report, Ford Aerospace Communications Corporation, January 1985.

[2] Mobile Satellite Configuration Study, Final Oral Reports, RCA Astro-Electronics, January 23, 1985.

APPENDIX A

MODULATION AND PERFORMANCE

A.0 INTRODUCTION

The MSAT system concept adopts the generic channel spacing of 5 kHz. Various modulation and/or coding schemes have been considered for use with the 5 kHz channel spacing. Figures A-1 and A-2 and Tables A-1 and A-2 present the C/N_0 or E_b/N_0 requirements for various modulation and coding schemes for 5-kHz channel spacing. Table A-1 and Figure A-1 excerpts from "MSAT-X System Definition and Functional Requirements" [1]. Figure A-2 is from "MSAT Mobile Terminal Study," Vol. 1 [2] by Canadians and Table A-2 is from [3].

Even though the required SNR's in Figures A-1 and A-2 and Tables A-1 and A-2 are a little different from each other, there is some common ground:

(1) Voice transmission may use Amplitude Compandored Single Sideband (ACSB) or digital voice, e.g., LPC (2400 BPS), with a bandwidth efficient modulation;

(2) Digital data (2400 BPS) may be used with a bandwidth efficient modulation. The bandwidth efficient modulation could be Minimum Shift Keying (MSK), Gaussian Minimum Shift Keying (GMSK), or Rectangular Spectrum Modulation (RSM).

All the required C/N_0 or E_b/N_0 numbers in Figures A-1 and A-2 and Tables A-1 and A-2 are required values in the absence of fading. The fading margin is to be accounted for separately in the link design. However, these required E_b/N_0 will vary drastically for various fading conditions and demodulation schemes.

TABLE A-1. End-to-End C/N_0 Requirements

Service	Description	Toll/Full Quality C/N_0	Minimum Quality C/N_0
ACSB Voice	4:1 Amplitude Compandored Single Sideband 3.4 kHz IF Bandwidth 5.0 kHz Channel Bandwidth Toll Quality is possible	50.3 dB Hz	33.0 dB Hz (Reference 8)
LPC Voice	Linear Predictive Coded Voice GMSK, 2400 BPS, Uncoded BT = 0.5 5.0 kHz Channel Bandwidth 10^{-3} BER = Full Quality 2×10^{-2} BER = Minimum Quality	44.8 dB Hz	40.8 dB Hz
Data	Digital Data GMSK, 2400 BPS, Uncoded BT = 0.5 5.0 kHz Channel Bandwidth 10^{-6} BER = Full Quality 10^{-5} BER = Minimum Quality	49.0 dB Hz	48.0 dB Hz

TABLE A-2. Proposed Link Margins

Modulation	(E_b/N_0) avg.	(E_b/N_0) peak	Nominal C/N_0 avg.	Margin	C/N_0 with Margin
SSB	11 dB	22 dB	45 dB/Hz	10 dB	55 dB/Hz
ACSB	11 dB	16 dB	45 dB/Hz	10 dB	55 dB/Hz
MSK/QPSK (2400 baud/s)	12 dB for BER = 10^{-6}	14.5 dB	46 dB/Hz	10 dB	56 dB/Hz
RSM* (2400 baud/s: data or LPC Voice)	11 dB for BER = 10^{-6}	14 dB	45 dB/Hz	10 dB	55 dB/Hz

*RSM - Rectangular spectrum modulator, a proprietary technique of Skylink Corp.

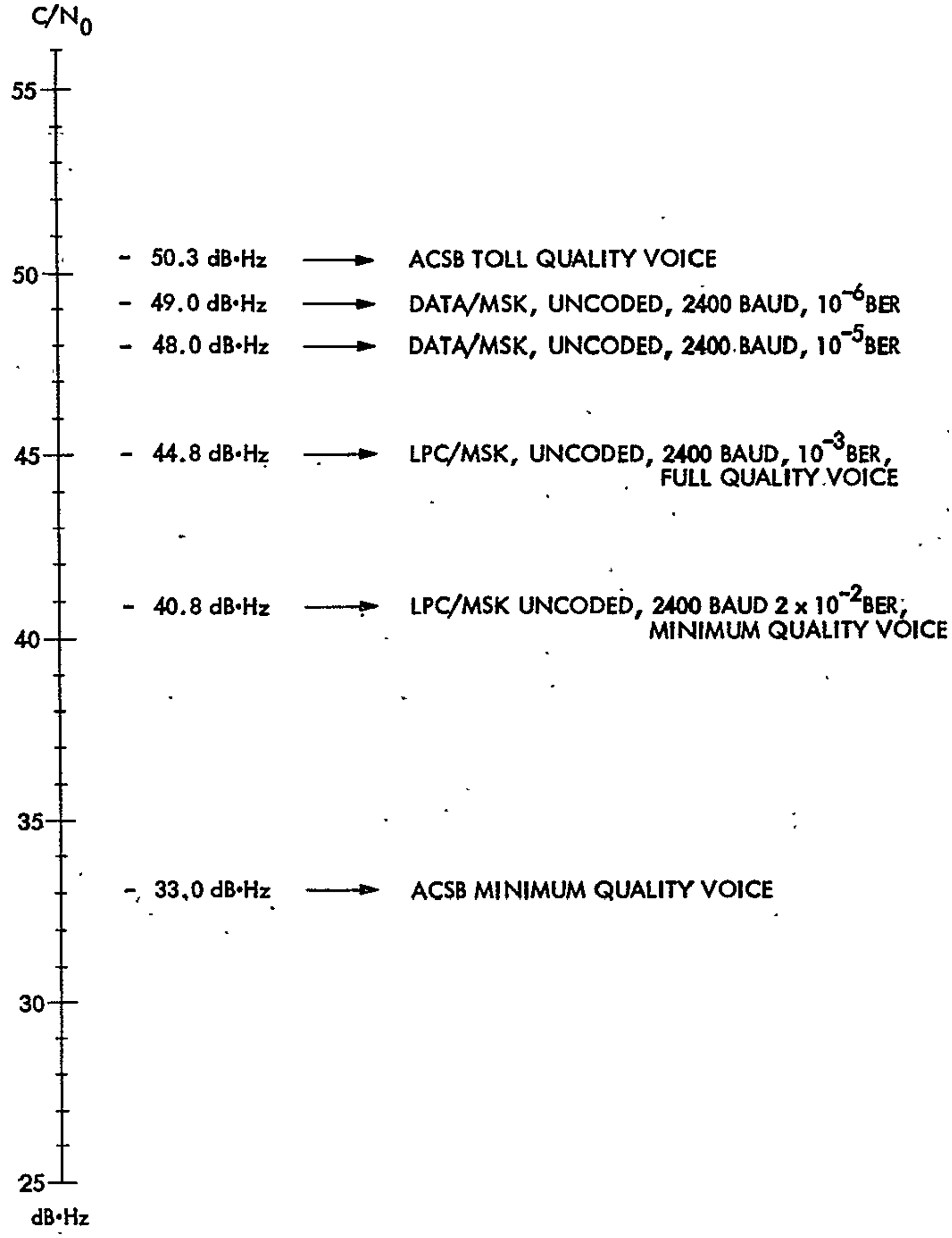
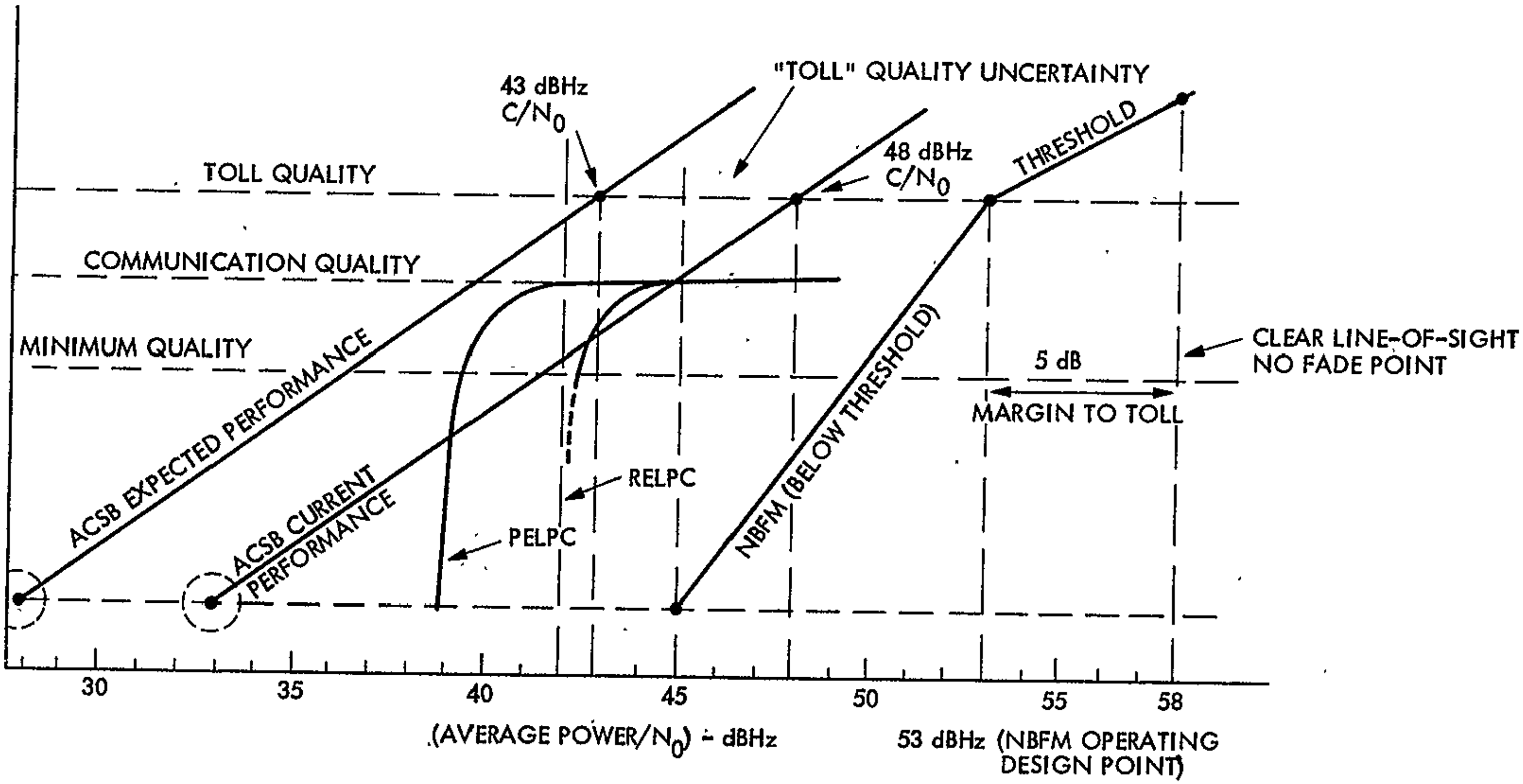


Figure A-1. Useful Range of Received C/N_0



NOTE: ACTUAL LEVELS WILL VARY DEPENDING UPON PARTICULAR IMPLEMENTATION TECHNIQUE.

Figure A-2. Variation Speech Quality With $C(N_0 + I)$

MSAT-2 baseline design assumes a digital modulation. Both MSK and GMSK have been investigated by MSAT-X for MSAT applications. The following sections discuss these two modulation schemes and the detection methods.

A.1 MSK VS. GMSK

MSK, which is binary digital FM with a modulation index of 0.5, has several good properties and coherent detection capabilities. (However, it does not satisfy the severe requirements with respect to out-of-band radiation for SCPC mobile radio.) MSK can be generated by direct FM modulation. As is easily found, the output power spectrum of MSK can be manipulated by using a premodulation low-pass filter (LPF), keeping the constant envelope property, as shown in Figure A-3. To make the output power spectrum compact, the premodulation LPF should have the following properties:

1. Narrow bandwidth and sharp cutoff
2. Low overshoot impulse response
3. Preservation of the filter output pulse area which corresponds to a phase shift $\pi/2$.

Conditions should be met which: 1) suppress the high-frequency components; 2) protect against excessive instantaneous frequency deviation; and, 3) allow coherent detection to be applicable as simple MSK [4].

"A Gaussian LPF satisfies all the above-described characteristics. Consequently the modified MSK modulation using a premodulation Gaussian LPF can be expected to be an excellent digital modulation technique" [4].

Figure A-4 shows the power spectra of GMSK where the normalized 3-dB band-

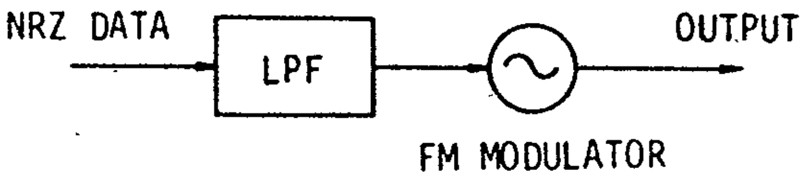


Figure A-3. Premodulation Baseband-Filtered MSK [4]

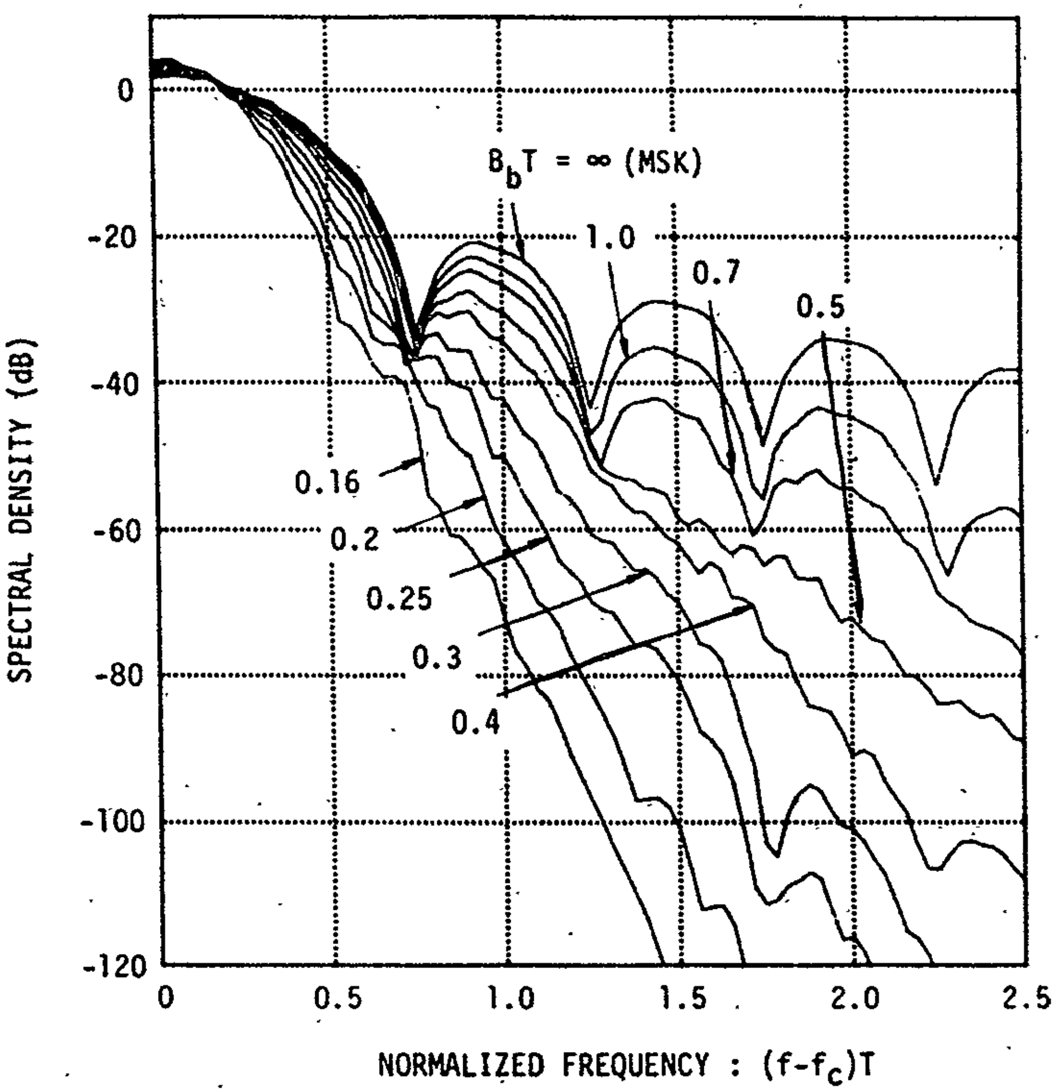


Figure A-4. Power Spectra of GMSK [4]

C-5

width of the premodulation Gaussian LPF, B_bT, is a parameter. Figure A-5 shows the fractional power in the desired channel with respect to the normalized bandwidth of the predetection rectangular bandpass filter (BPF), B_iT, for various B_bT's.

Figure A-6 shows the ratio of the out-of-band radiation power in the adjacent channel to the total power in the desired channel with respect to the normalized channel spacing.

Figure A-7 presents a typical bit error-rate performance for GMSK of various B_bT in the absence of fading. A coherent detection is employed.

The tradeoff of bandwidth and the performance is obvious by comparing Figures A-6 and A-7. By reducing the LPF bandwidth B_b, we can reduce the channel spacing, fs, with a fixed adjacent channel interference level. However, the bit error-rate performance (Figure A-7) degrades. After some optimization process, $B_bT = 0.5$ is generally accepted for the MSAT project [5] in the presence of Rician fading.

A.2. COHERENT DETECTION VS. DIFFERENTIAL DETECTION

In the absence of fading, it is well known that the coherent detection has an advantage over the differential detection in bit error-rate performance (Figure A-7). However, there is a lack of analytical or experimental data comparing the coherent detection and differential detection in the exact fading conditions. It is believed that the differential detection will perform more adequately than the coherent detection. In this section, some of the data available will be presented as is.

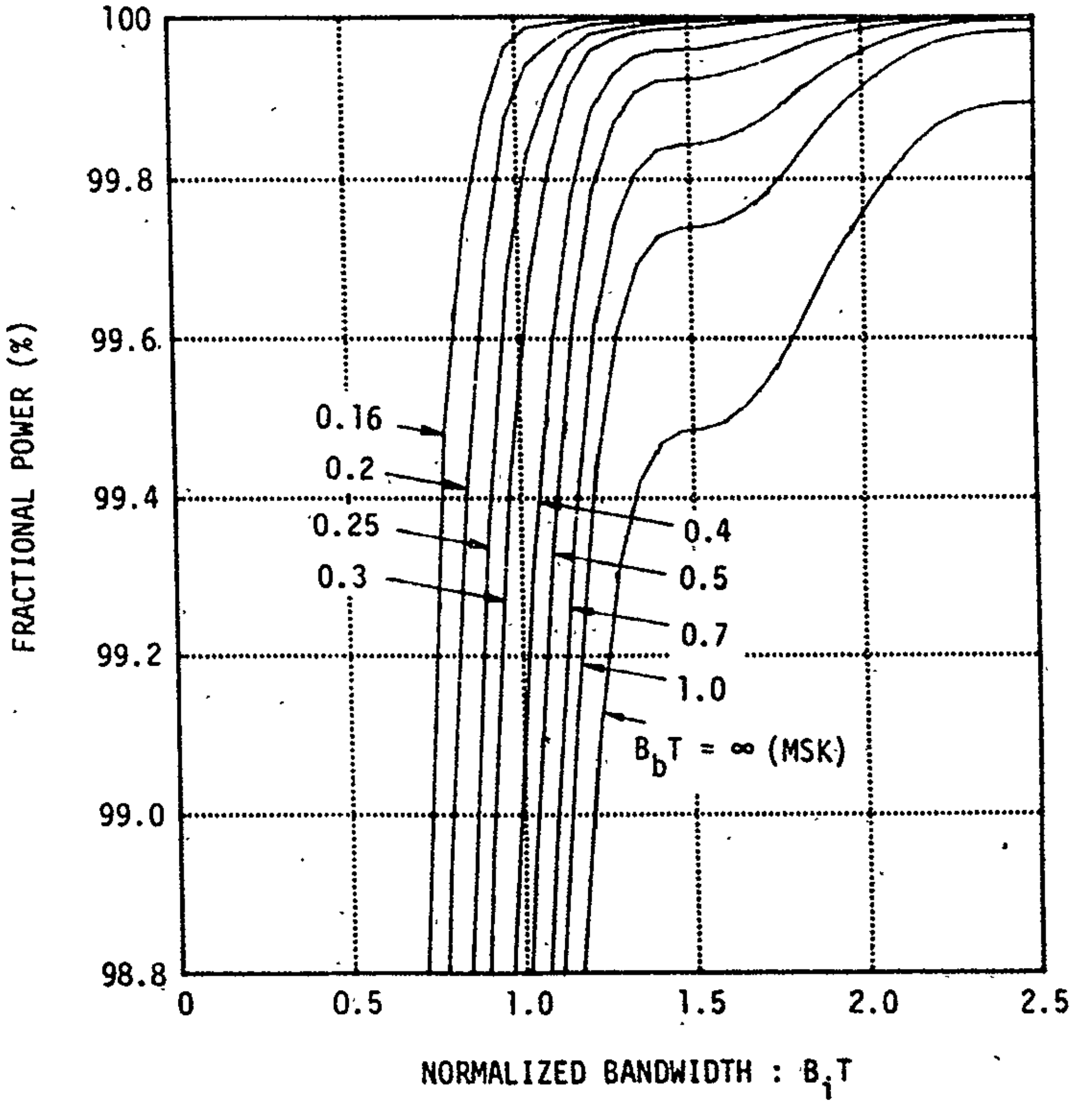


Figure A-5. Fractional Power Ratio of GMSK [4]

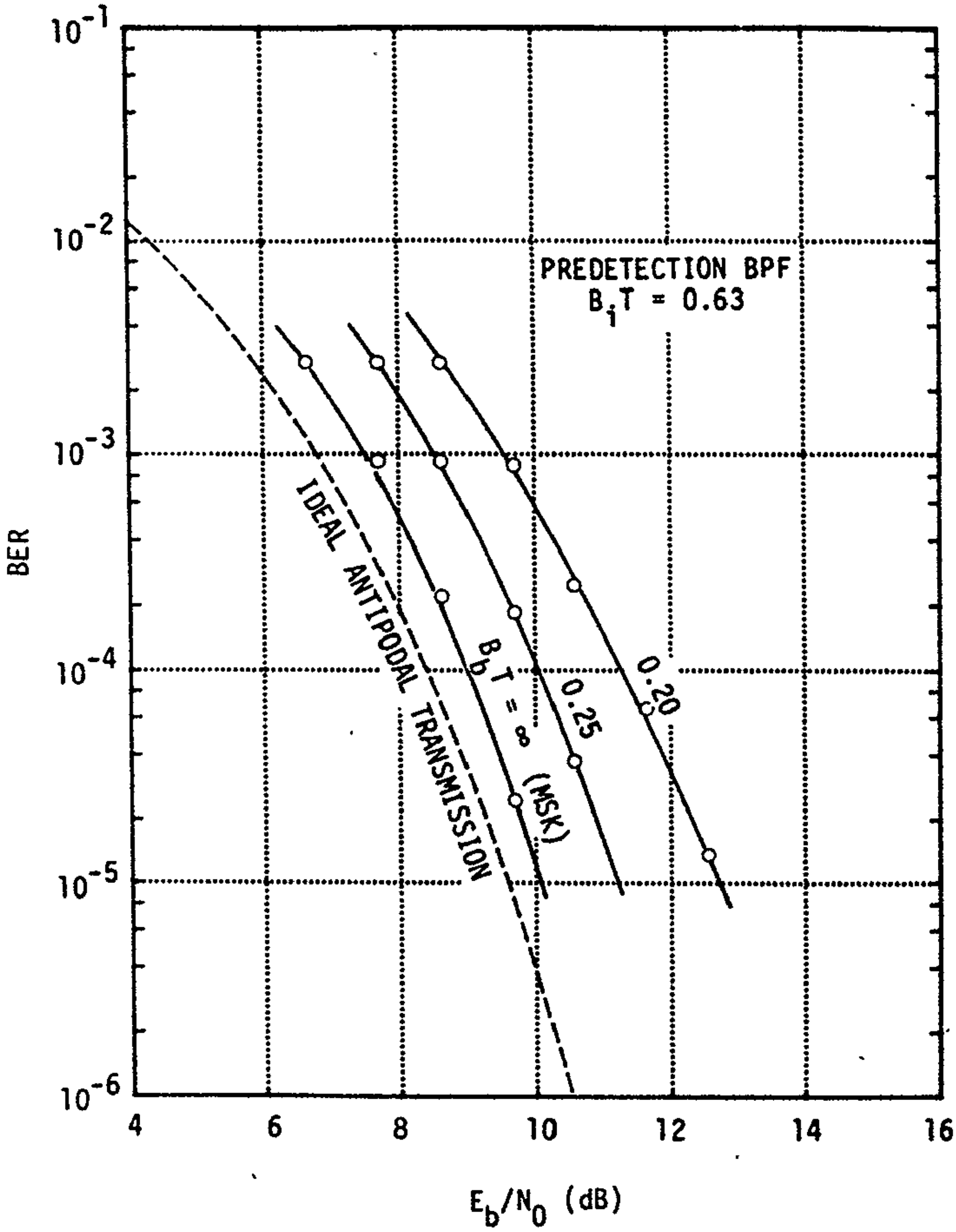


Figure A-6. Static BER Performance [4]

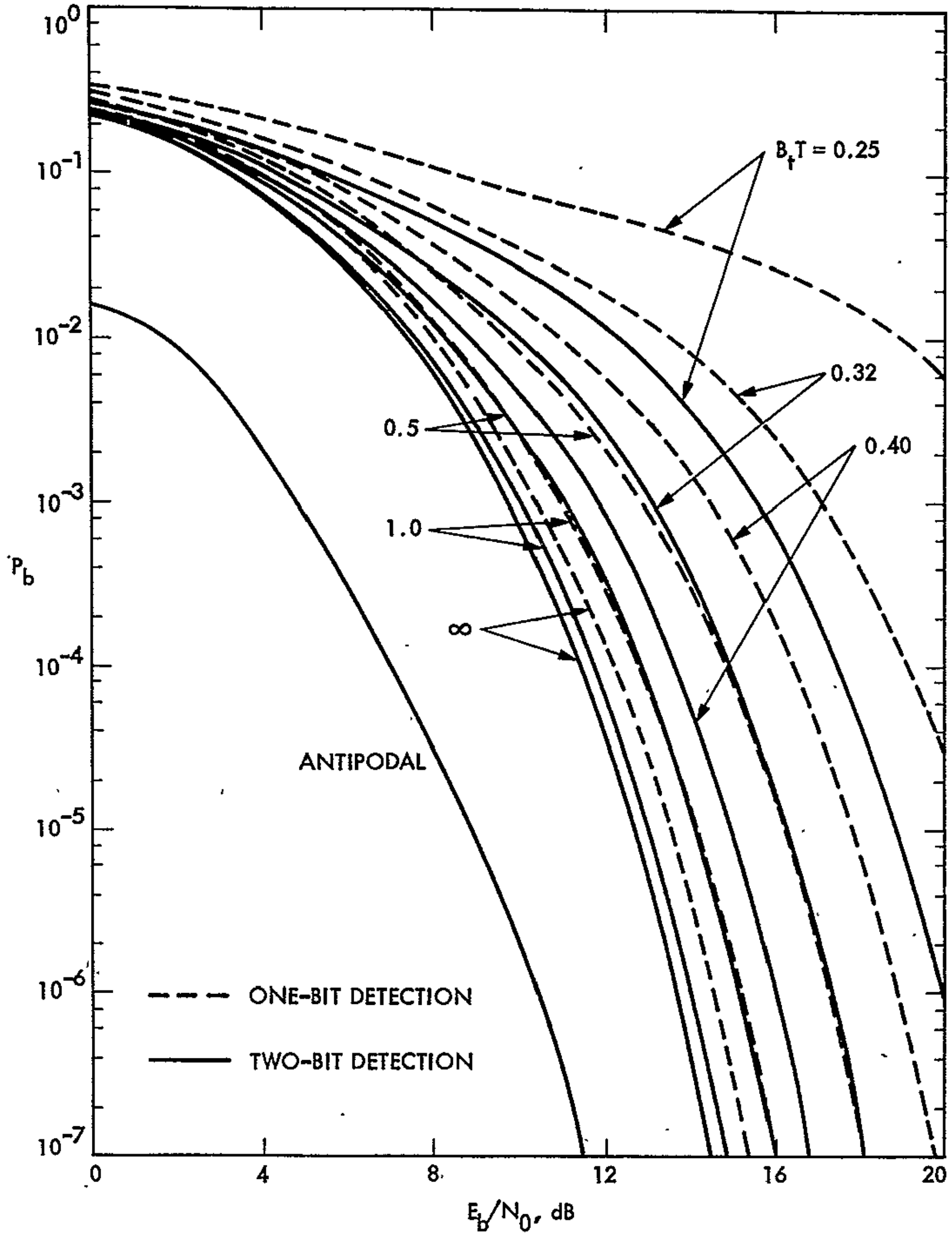


Figure A-7. Performance of One- and Two-Bit Differential Detection of GMSK. Receiving B_rT is optimized for Each B_tT. (For a Two-Bit Detection Case, the Detection Threshold is Optimized for Each E_b/N_0.) [5]

The paper by Hirade [6] asserts as follows: "Though the error-rate performance of differential detection is slightly inferior to that of coherent detection, the receiver structure is greatly simplified since it does not require the complicated phase-locked loop carrier recovery circuit, and only a simple delay line with time delay equal to the signaling interval is used to provide a direct estimate of the phase difference. It is not easy to construct a simple carrier recovery circuit which enables one to regenerate the reference carrier precisely and stably in the fast Rayleigh fading channels such as UHF or microwave land mobile radio channels." Also, an unpublished JPL memo cites that: "Coherent signal detection in multipath fading channels is only possible at the expense of enlarged carrier tracking loop bandwidth, degrades static performance of the receiver but improves the error floor associated with fading links. Another drawback of coherent reception in mobile links is its finite (non-zero) time requirement to recover from a deep fade. Differentially coherent receivers, on the other hand, do not suffer from such disadvantages in the fading channels. Although the static performance of a differential detector is inferior to its coherent counterpart, nevertheless, its dynamic behavior in mobile links is robust. Simplicity is another good attribute of differential detectors."

Even though there have been many papers addressing the performance of coherent detection and differential detection of MSK, FSK, or GMSK, most of the data were taken under different parameters and conditions. Thus, it is hard to compare the performance of the coherent detection and differential detection precisely.

For the sake of reference, some of the BER performance curves are included here. Figure A-8 is the latest experimental data obtained at JPL. The performance curves are for a 2-bit differential detection of differentially encoded GMSK signal. Three cases of fading conditions were used for testing: Rayleigh fading, Rician fading with 20-Hz doppler, and 72-Hz doppler where the ratio (K) of the line-of-sight signal and the diffused signal is 10 dB. The condition with F_0 = 20 Hz and K = 10 dB is believed to be a typical condition encountered by land mobile terminals in the rural environment. (F_0 denotes the doppler frequency.)

Figures A-9 through A-13 are some indiscriminate collections of digital FM continuous phase FSK or GMSK. Comparing Figures A-9 and A-10, and A-11, it can be concluded that the error floor (the bit error-rate level where an increase of the SNR will not improve the BER performance) for the differential detection is much lower than that of the coherent detection at least in the Rayleigh fading condition. However, it is not clear whether that is true in the Rician fading conditions. In Figures A-12 and A-13, the dramatic performance difference between coherent and differential detection seems less pronounced in Rician fading condition with K = 10.

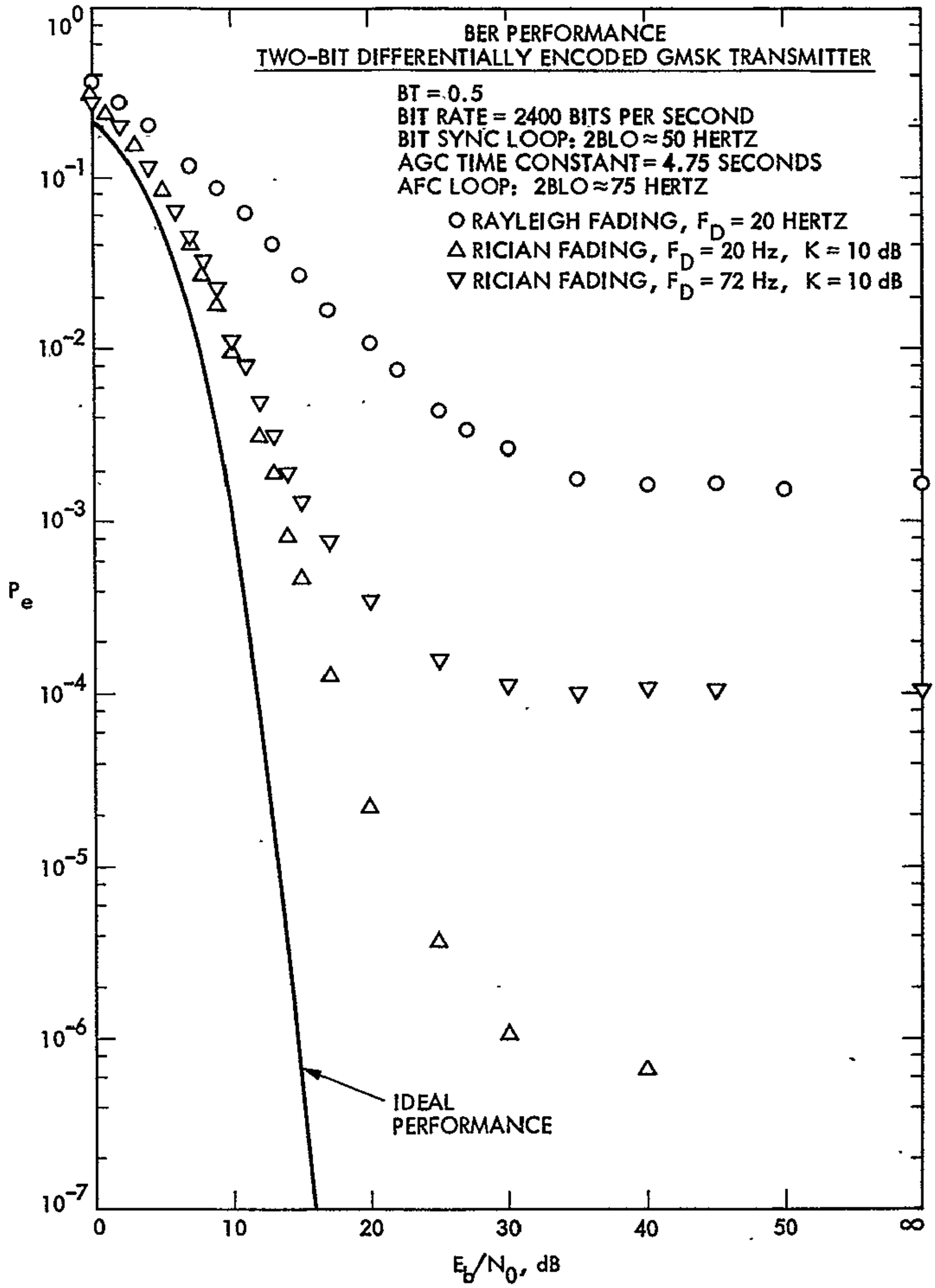


Figure A-8. Two-Bit Differential Detection of GMSK

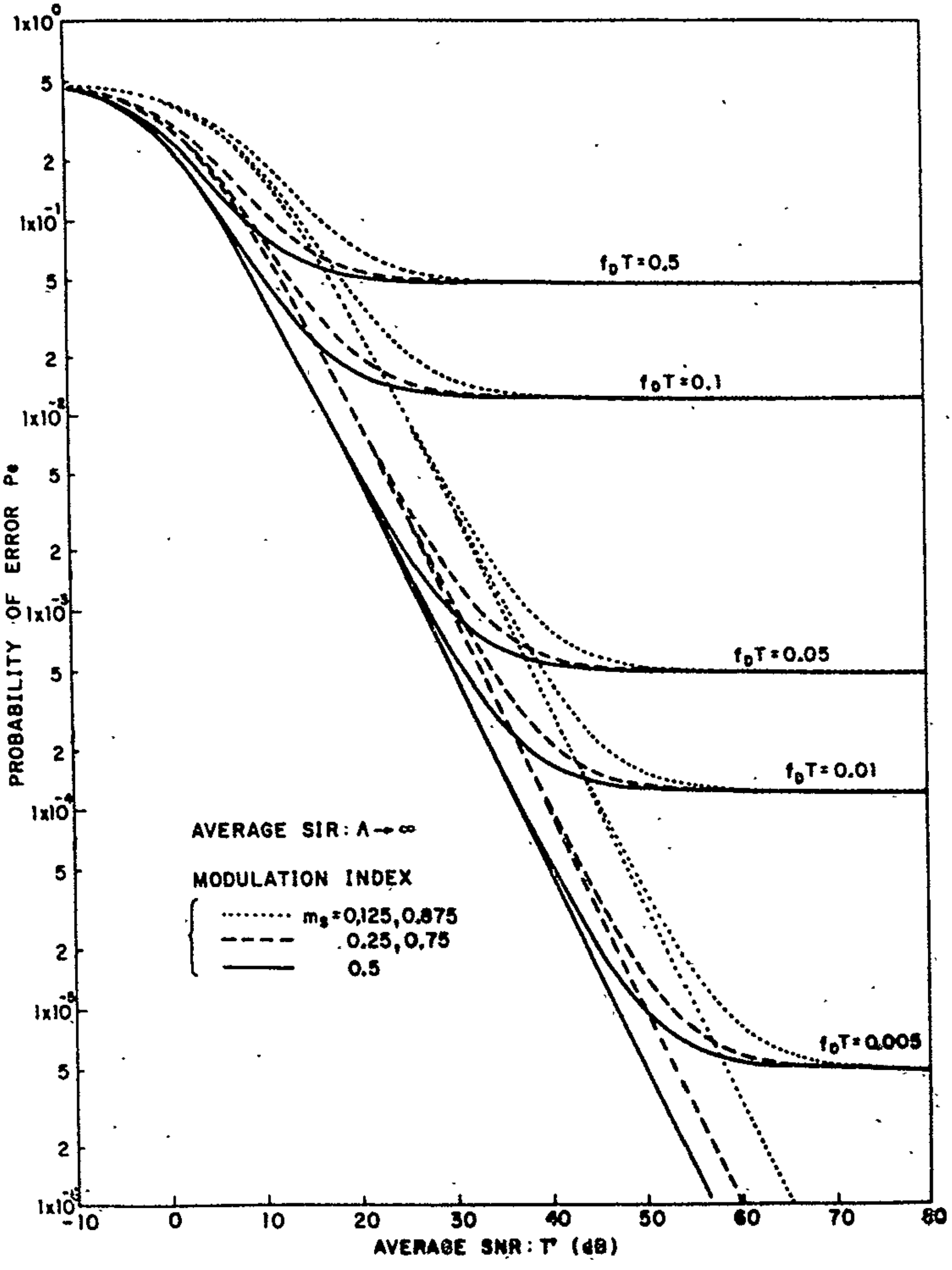


Figure A-9 . Error-Rate Performance of Digital FM With Differential Detection in Fast Rayleigh Fading Environment [6]

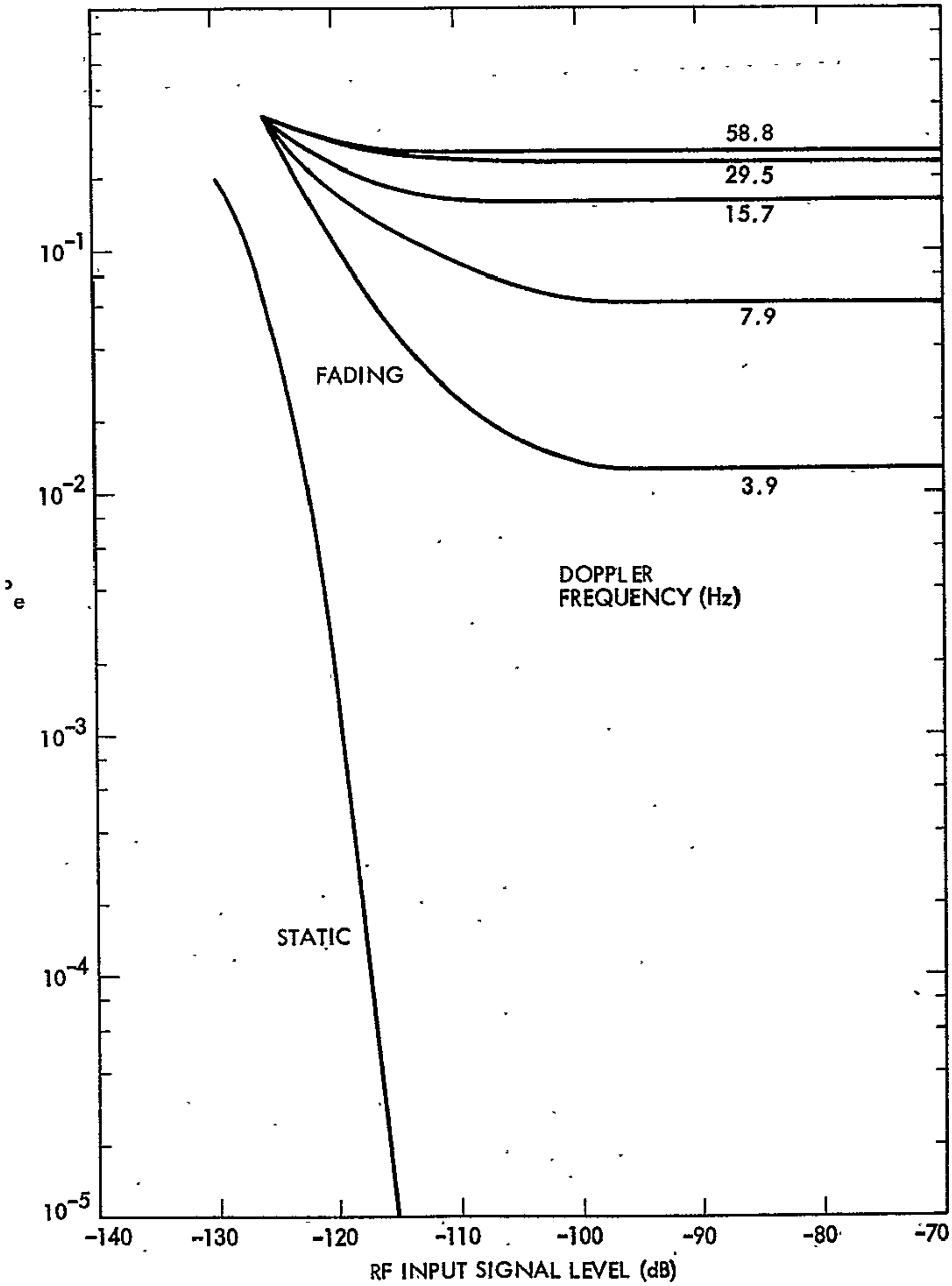


Figure A-10. BER Performance of 0.2 GMSK Receiver [7]

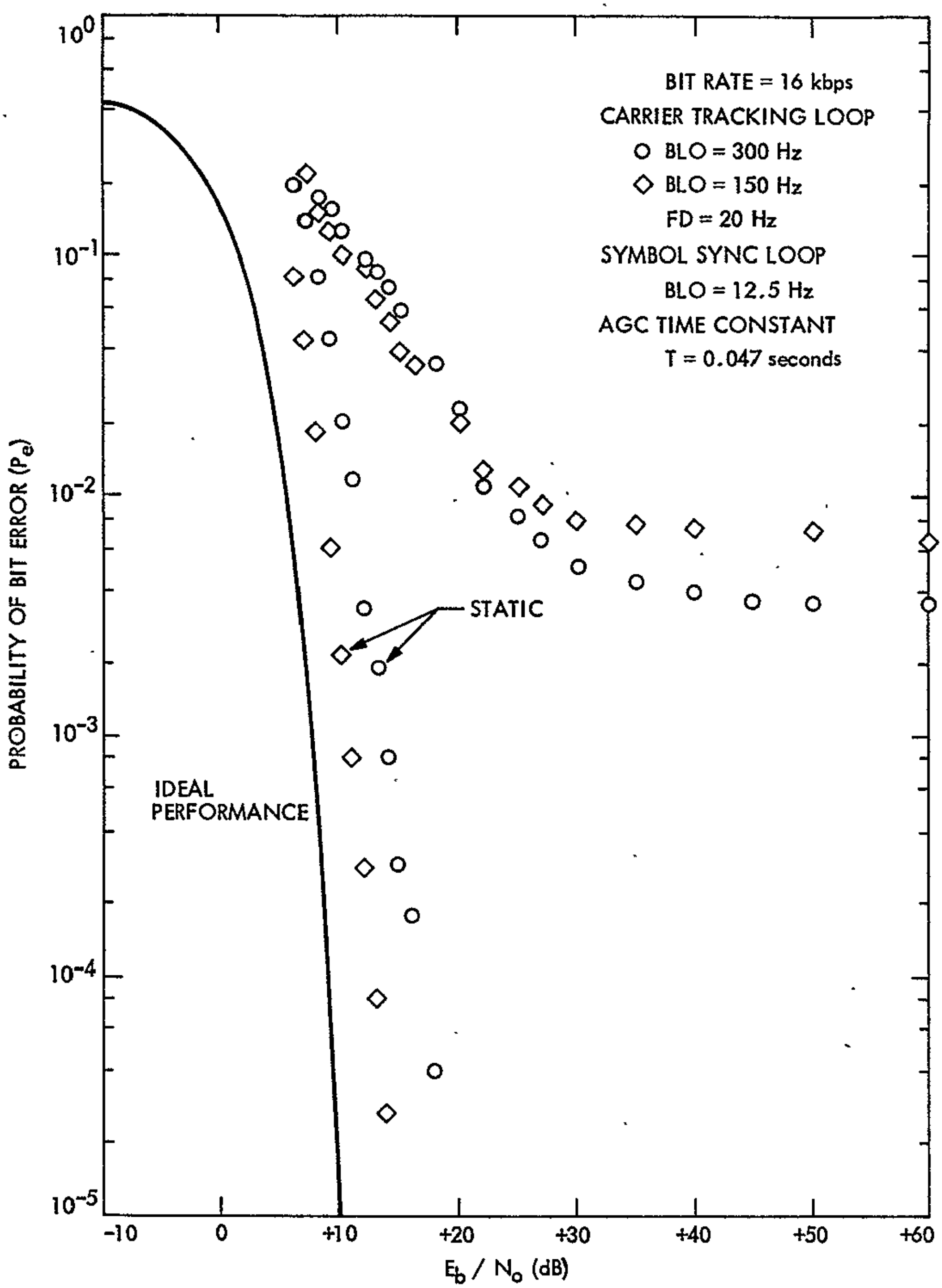


Figure A-11. Measured Bit Error Rate for Coherent Demodulation of Differentially Encoded 16-KPBS MSK Signal Fading Channel With Doppler Frequency of 20 Hz [1]

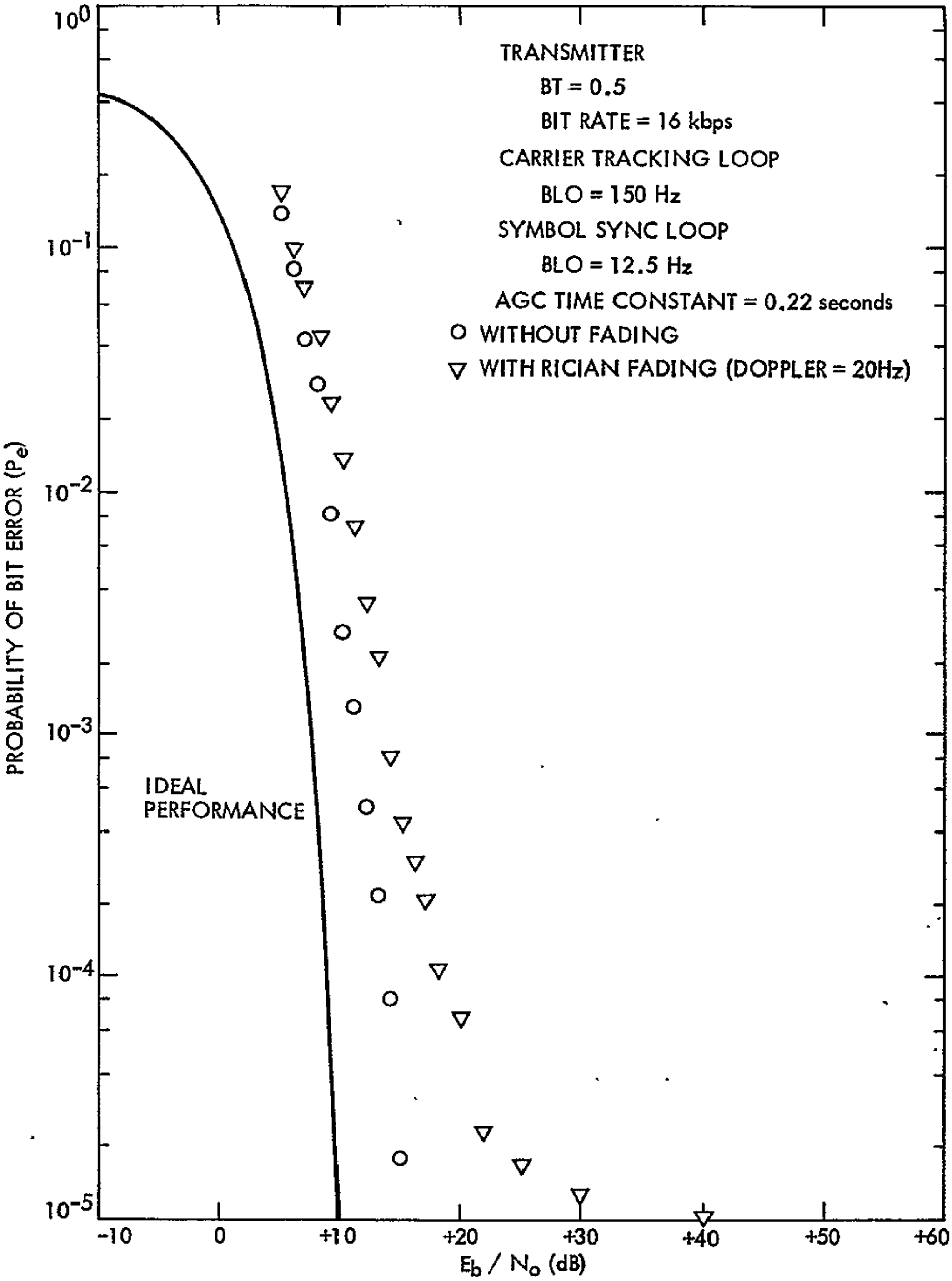


Figure A-12. Measured Bit Error Rate of GMSK Over a Channel With Coherent Demodulation (Differential Encoding is Inherent) [1]

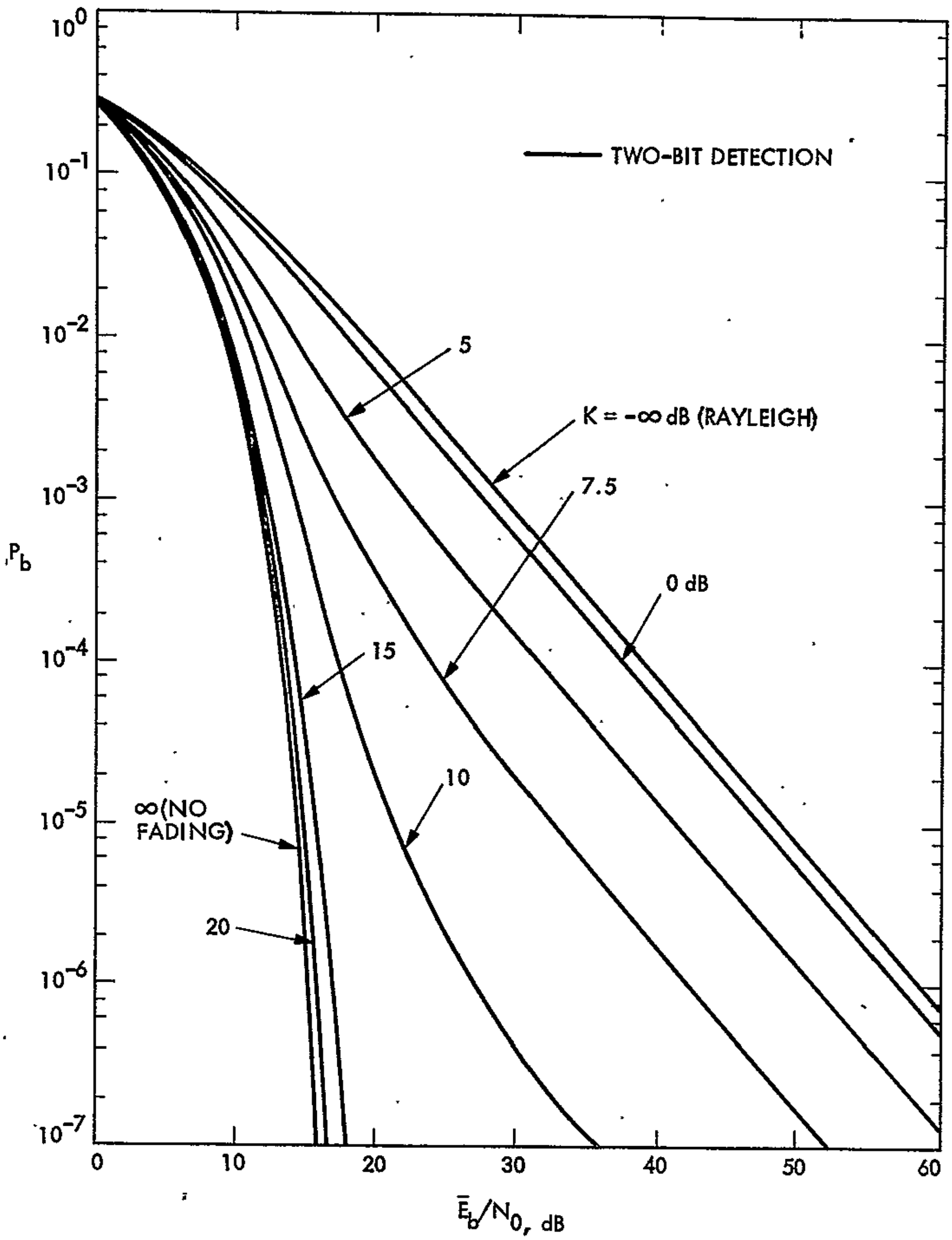


Figure A-13. Average Bit Error Rate Performance of Two-Bit Differential Detection of GMSK Over a Rician Fading Channel. BT = 0.5.

REFERENCES

[1] Bell, D. J., Townes, S., "MSAT-X System Definition and Functional Requirements," JPL D-1709 (internal document), Rev. 2, Jan. 10, 1985.

[2] Bashir, A. J., et al., "MSAT Mobile Terminal Study," Final Report Vol. 1, DOC-CR-SP-82-034, ADGA Systems Int. Ltd. for Department of Communications, Ottawa, Canada, April, 1982.

[3] King, J., "Skylink Readies Its Thin-Route Mobile Satellite Service," Microwave & RF, August 1984.

[4] Murota, K., et al., "GMSK Modulation for Digital Mobile Radio Telephony," IEEE Trans. on Communications, Vol. COM-29, No. 7, July 1981.

[5] Simon, M. K., Wang, C., "Differential Detection of Gaussian MSK in a Mobile Radio Environment," IEEE Trans. Vehicular Tech., November, 1984.

[6] Hirade, K., et al. "Error-Rate Performance of Digital FM With Differential Detection in Land Mobile Radio Channels," IEEE Trans. Vehicular Tech., Vol. VT-28, No. 3, August 1979.

[7] Goode, S. H., "A Comparison of Gaussian Minimum Shift Keying to Frequency Shift Keying for Land Mobile Radio," 34th IEEE Vehicular Technology Conf., 1984.

APPENDIX B

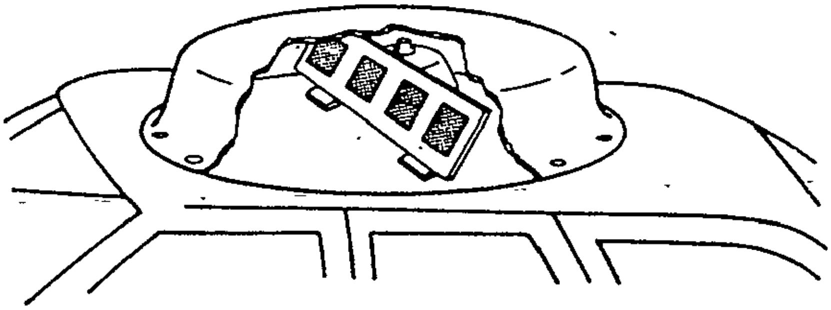
CHARACTERISTICS OF SOME MOBILE ANTENNAS

3.0 INTRODUCTION

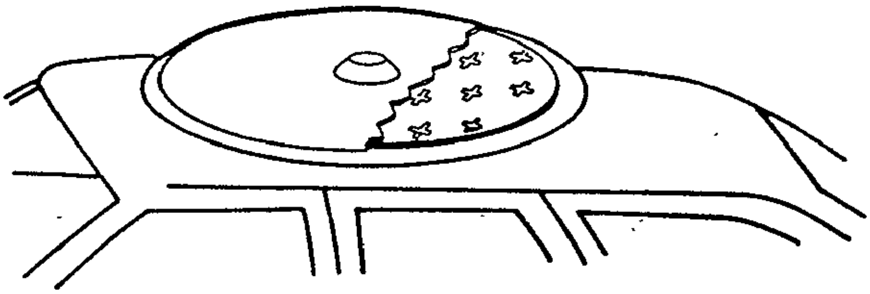
Various types of antenna have been investigated by MSAT-X for possible applications to the mobile terminals. This appendix presents some of the results. Due to the nature of the mobile antenna study, results presented in this appendix, although being the best available estimates, should be considered as preliminary and are subject to future modifications. Three types of mobile antenna have been explored by various companies for mobile applications: low-gain antenna (LGA), medium-gain antenna (MGA), and high-gain antenna (HGA). The gain of the LGA is approximately 4 to 6 dB. The LGA in general is simpler and less expensive than the MGA and HGA. The estimated cost to the customer for a LGA is roughly $50, if mass produced. The LGA, however, does not provide enough discrimination against adjacent satellites in a multi-satellite environment. The gain of the HGA is approximately 16 to 20 dB. The use of the HGA would significantly reduce the burden on the spacecraft. However, the HGA is not practical for mobile vehicles because of its size. The gain of the MGA, which is the MSAT-2 baseline antenna, is about 10 to 12 dB. Currently, three types of MGA are being investigated for mobile applications (Figure B-1):

1) Mechanically steerable 1 X 4 titled array
2) Mechanically steerable conformal array, and
3) Electronically scanned conformal phased array.

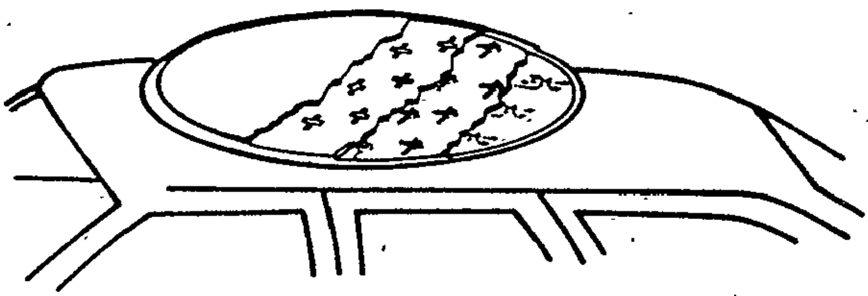
Each of these antennas will be discussed in the following sections.



Mechanically Steered 1 x 4 Tilted Microstrip Array



Mechanically Steered Fixed-Beam Conformal Array



Electronically Steered Conformal Array

Figure B-1. Three Types of Medium-Gain Mobile Antenna Configured Atop a Car Roof [1]

B.1 MECHANICALLY STEERABLE 1 X 4 TILTED ARRAY

This antenna contains a 1 X 4 linear microstrip array covered by a radome (Figure B-2). The array is tilted at an angle to provide the desired elevation pattern. The overall dimension of the antenna (at UHF), including the radome, is about 7 inches high and 33 to 36 inches in diameter [1, 2]. The gain of the antenna is approximately 10 to 11 dB over CONUS. The half-power beamwidth (HPBW) is about 18 degrees in the azimuth direction, and about 65 degrees in the elevation direction. Since the azimuthal beamwidth is considerably narrow, some sort of tracking mechanism will be required for mobile applications.

The projected intersatellite isolation for this type of antenna is approximately 15 to 20 dB for a 2-satellite operation, and about 12 dB for a 3-satellite environment. Because of the low intersatellite isolation, operating this type of antenna in a 3-satellite situation is difficult.

When produced in a large quantity, the estimated cost of this type of antenna (to the customer) is approximately $600 to $800, including the installation charge.

Because of the relatively narrow azimuthal beam, tracking in the azimuthal direction is necessary. Various tracking schemes have been proposed including single channel monopulse tracking, magnetometry, and gyro-aided monopulse tracking [1, 2].

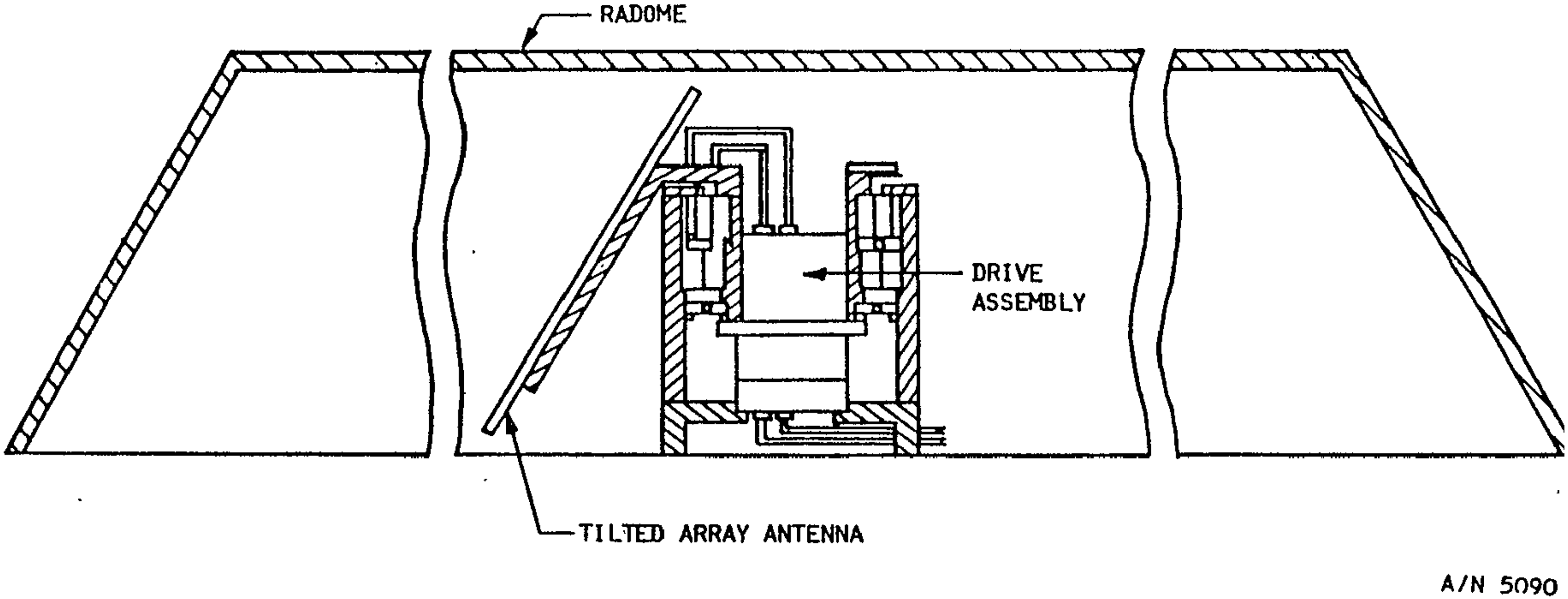


Figure B-2. Mechanically Steerable 1 X 4 Nonconformal Tilted Array and its Drive Assembly [1]

B.2 MECHANICALLY STEERABLE CONFORMAL ARRAY

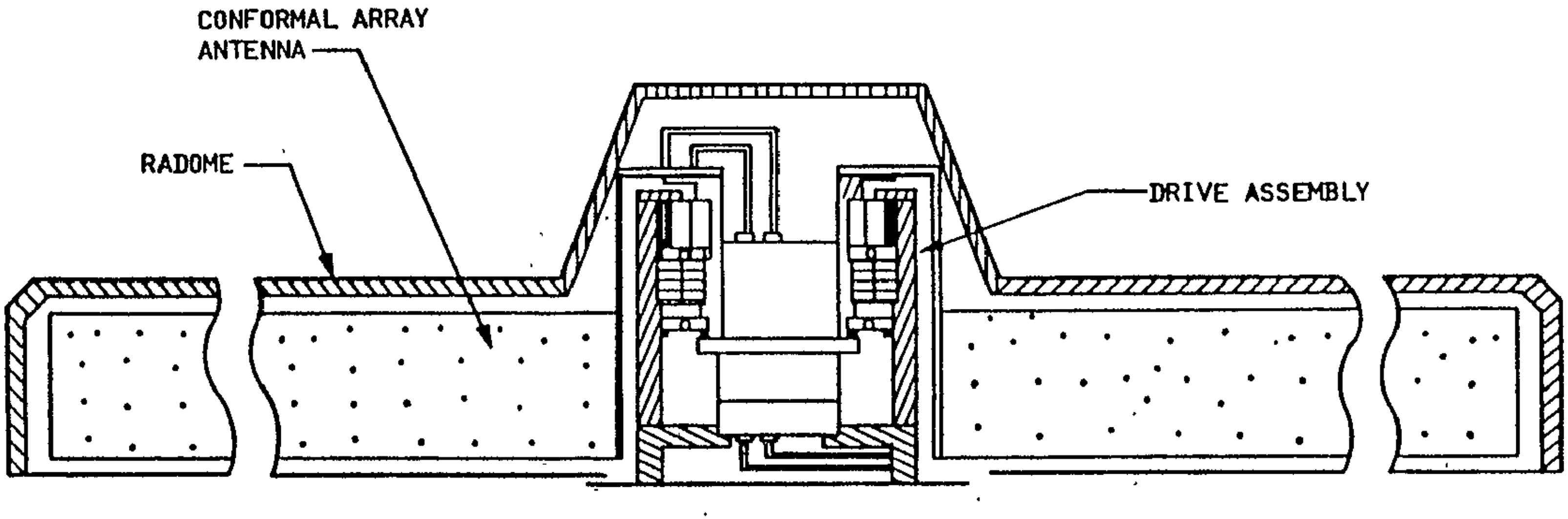
Figure B-3 shows a conformal mechanical antenna and its drive assembly. The conformal array is designed using stripline-fed crossed slots. This antenna has an estimated height of about 3.5 inches and a diameter of 36 inches.

The HPBW in the azimuthal direction is 26 degrees. Similar to the 1 X 4 tilted array, the beamwidth in the elevation direction is relatively broad.

The adjacent satellite isolation for this antenna is about 20 dB for a 2-satellite environment, including polarization diversity. The customer cost of this antenna is estimated to be $1200 to $1300, including installation charges and on a mass production basis. Similar to the nonconformal mechanical antenna, tracking is required in the azimuthal direction.

B.3 ELECTRONICALLY SCANNED CONFORMAL ARRAY

A picture of the electronically steered conformal phased array is shown in Figure B-4. This antenna is designed using stripline-fed cross slots and phase shifters. Among the three types of MGA, this antenna has the lowest profile, estimated to be about 2 inches, making it physically more suitable for mobile applications. This type of antenna, however, is expensive. The estimated customer cost is $2200 to $2300 at a mass production level (100,000 units or more).



A/N 5090

Figure B-3. Conformal Mechanically Steerable Antenna [1]

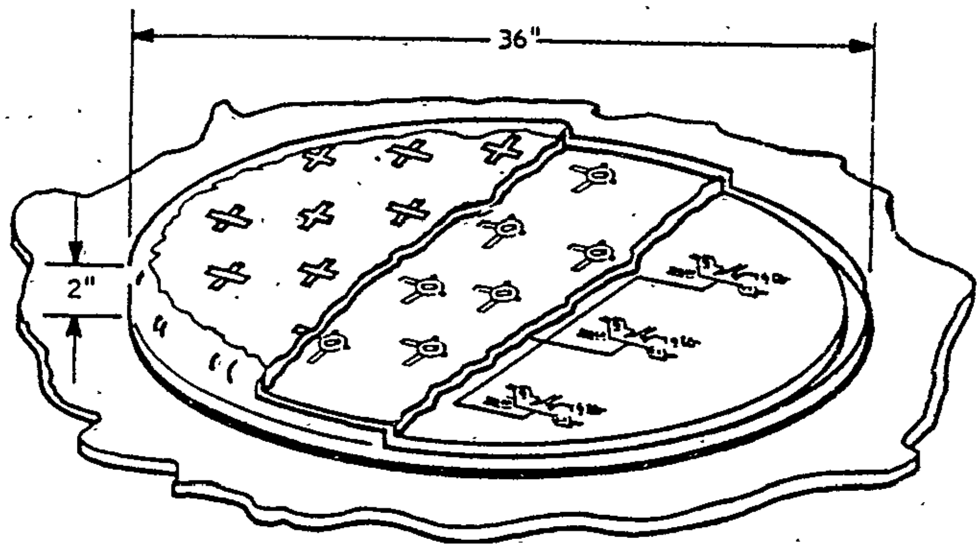


Figure B-4. Electronically Steerable Conformal Phased Array [1]

REFERENCES

[1] Land Vehicle Antennas for Satellite Mobile Communications, Final Report, Ball Aerospace System Division, F 85-02, February 1985.

[2] Mobile Antenna and Beam Pointing Studies for Satellite Mobile Communications, Final Report, Cubic Cooperation, TR/209-3, February 6, 1985.

APPENDIX C

A SIMPLE USER COST MODEL

C.0 INTRODUCTION

This appendix presents a simple user cost model. It is simple in that it is easy to understand and easy to use. It has been implemented as a computer program called the MSS FINANCE.RPT. This program is written in the spreadsheet language Multiplan* and runs under the MS-DOS* operating system on the IBM PC and "IBM PC-compatible" microcomputers. FINANCE.RPT has been submitted to, and may be obtained from, COSMIC**.

FINANCE.RPT computes the prices that a Mobile Satellite System (MSS) company would have to charge to meet all of its expenses and make a specified profit (rate of return on equity capital). It also analyzes an MSS user's finances, producing a figure of merit that can be used to compare alternative system designs.

Section C.1 presents a brief overview of the spreadsheet layout. Section C.2 gives a brief tutorial on relevant topics in engineering economics and serves to clarify the terminology to be used in the subsequent sections. Sections C.3 - C.6 provide the analysis of the MSS supplier's finances, which leads to

---

*Multiplan and MS-DOS are registered trademarks of the Microsoft Corporation, 10700 Northup Way, Bellevue, WA 98004.

**COSMIC, the Computer Software Management and Information Center, Barrow Hall, University of Georgia, Athens, Georgia 30601, is the repository for computer programs, developed within NASA, which may be useful in a wider context.

the determination of required user charges. Section C.7 concludes this appendix by offering the analysis of customer finances, leading to the figure of merit that incorporates the costs of customer equipment as well as user charges.

C.1 OVERVIEW OF THE FINANCE.RPT SPREADSHEET

A spreadsheet program consists of an array of cells, of which only a few can be seen on the monitor at any one time. The cursor can be moved to bring different parts of the spread sheet into view.

Some of the cells contain labels to make the sheet easier to read, but most cells contain numbers. The cells that show output numbers also contain formulas that determine how to combine the numbers from other cells.

Inputs and outputs can be readily distinguished on the screen or on a printed copy of the spread sheets: Labels for inputs are followed by a colon (:); labels for outputs have equals signs (=).

The FINANCE.RPT spread sheet is laid out in four areas as described in the caption to Figure C-1.

C.1.1 Principal Outputs

A few of the numbers calculated are of considerably more interest than others.

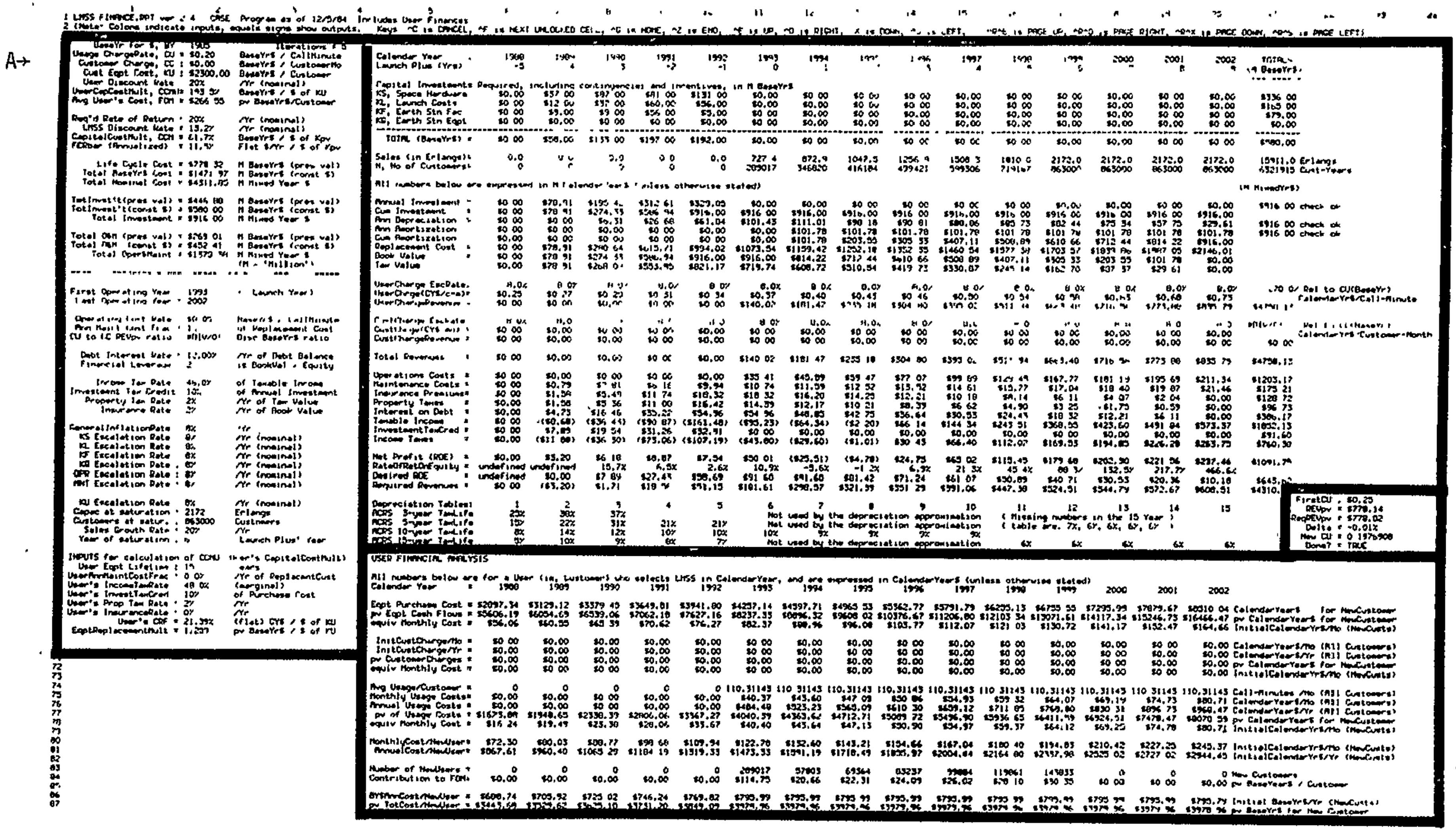


Figure C-1. Layout of the FINANCE.RPT Spreadsheet Program for Determining the Financial Consequences of Alternative Designs for Mobile Satellite Systems

A: Summary Outputs and Scalar Inputs

B: Year-By-Year Suppliers' Investment Inputs and an Analysis of Suppliers' Finances

C: Iteration Control Block

D: Analysis of Customers' Finances

Supplier's Finances:

- o Usage Charge Rate, CU. This is the amount that the supplier must charge to produce enough revenue to meet all expenses and make the specified profit. The amounts actually charged each year are inflated according to the escalation rates which are input.

  The supplier also obtains revenue from the Customer Charge, CC, an input. Note that if CC produces too much revenue, CU can come out negative.

- o CU to CC REVpv ratio. This is the ratio of the present values of the revenues obtained from the two sources.

- o The supplier's total cost over the life of the project is expressed in three different forms. The Life Cycle Cost is perhaps the most meaningful: the present value. The Total BaseYr$ Cost measures the resources required, but loses the impact of the time value of money. The Total Nominal Cost is the sum of the inflated cash flows - the number that would be seen in the supplier's ledger at the end of the project.

Customers' Finances:

- o Avg User's Cost, FOM. This is the figure of merit by which alternative system designs should be compared. It includes all three components of user cost: equipment costs, connect charges, and usage charges.

- o BY$AnnCost/NewUser. This is the real levelized annual cost faced by a new MSS customer who subscribes in the indicated year, expressed in BaseYear$. To obtain the customer's actual cash outlays, this number must be inflated for the appropriate number of years.

- o pv TotCost/NewUser. This is the equivalent of the life cycle cost for a new customer. It is the amount he would need for investment should he choose to subscribe and then pay all of his expenses from the investment. Since it is expressed in constant BaseYear$, it would have to be inflated to the appropriate year if he were to actually buy such an annuity.

C.1.2 Limitations

The treatment of depreciation could be improved, particularly by using different tax lifetimes for the different categories of MSS system investment. Further, user equipment depreciation could incorporate the ACRS table instead of the current "straight-line" assumption. If this kind of detail were to be put into the calculation, it might also be desirable to use the correct corporate tax rate table, instead of a single "Income Tax Rate" number.

The current version does not distinguish between the two classes of users expected: voice and data. Incorporation of that distinction, along with a few additional assumptions, would permit the calculation of prices for both classes of users and, perhaps, for both kinds of charge (i.e., usage and subscription).

A major reduction in the size and running time of the program could be achieved by rederiving the USES equations (JPL Document 5040-29) and incorporating those results. The major reason for a rederivation is that it would set to rest the issue of what formula should be used to compute the supplier's discount rate, an issue on which financial analysts are not completely in agreement.

FINANCE.RPT is based on an assumed demand versus time function which is not affected by the resultant normative price estimates. In general, however, sales are dependent on prices. Development and incorporation of a pricing model taking this interaction into account would have required a significantly larger allocation of study resources.

C.2 USER CHARGE MODEL - ANALYSIS OF SUPPLIER'S FINANCES

The first two subsections consist of a brief tutorial on relevant topics in engineering economics, and may be skimmed rapidly by those readers who are already comfortable with economic analysis in the presence of inflation.

The remaining two subsections provide the theoretical basis for the determination of normative prices - the prices that a supplier must charge to cover all of his costs and make a specified profit.

C.2.1 Escalation and Inflation

The value of a specified amount of a particular good or service must be quantified to be useful in analysis. A meaningful way to quantify that value is

to determine the quantity of other goods or services that would be traded for it in a barter economy. Direct barter is, however, often very inconvenient: money provides a convenient intermediate "good" to facilitate trade. The value of a good can then be measured in terms of its price.

The price of a good is the best general measure of its value, but that measure has some characteristics that make it difficult to use. High on the list is the fact that prices change with time, not only due to changes in the relative values of goods, but also due to extraneous factors - such as how much money is in circulation.

The term <u>escalation</u> refers to the change of price with time. Economists use the term <u>real escalation</u> for the portion of that change which is due to a change in relative value. They refer to the unadjusted, observable change as <u>nominal escalation</u>.

<u>Inflation</u>, on the other hand, refers to the change in the measure itself. Thus, it is the average escalation of a collection of goods and services. Because the role of money is to serve as an intermediary in trades, the appropriate collection depends upon which goods and services are to be traded. Consequently, a variety of different indices are used: The Consumer Price Index is based on a "market basket" of goods presumably relevant to the average consumer. The Gross National Product Deflator is based on all of the goods and services that make up the GNP.

The adjectives nominal and real are used to qualify other terms as well. Thus, a nominal price (or, equivalently, a price expressed in nominal terms) is the price that would be used in the market place. A real price (or a price expressed in real terms) is a price from which the effects of inflation have been removed.

Real prices of different goods presumably express the relative values of those goods. Computation of a real price requires the specification of a base year. Such prices are then expressed in base year dollars. The following equations can be used for conversion between "real" and "nominal" quantities:

$$p_t = p_{t-1}(1+gx_{t-1}) = p_{BY} \prod_{i=BY}^{t-1}(1+gx_i) \tag{C-1}$$

$$= p_{BY}(1+gx)^{t-BY} \text{ if } gx_t = gx\text{, a constant} \tag{C-2}$$

$$p_t' = p_t / \prod_{i=BY}^{t-1}(1+g_i) \tag{C-3}$$

$$= p_t(1+g)^{BY-t} \text{ if } g_t = g\text{, a constant} \tag{C-4}$$

$$(1+gx_t) = (1+gx_t')(1+g_t) \tag{C-5}$$

where,

p_t = Price in year t, expressed in nominal terms.

BY = Base year.

p_{BY} = Price in the base year, expressed in nominal and in real terms.

p_t' = Real price in year t, expressed in base year dollars.

gx_t = Nominal escalation rate for goods or services of type x, expressed in fraction/year, during year t.

gx_t' = Real escalation rate.

g_t = Inflation rate, in fraction/year, during year t.

Equations (C-1) to (C-5) assume, as is the custom among financial analysts, that escalation and inflation occur in annual quantum leaps. A continuous formulation could be used instead, but there is no reason to expect the resultant integrals to provide a better model of the rather "noisy" real world.

As a side point, it may be interesting to note that p_t', the price in base year dollars, may not be equal to p_{BY}, the price in the base year, because the relative value of the good may have changed. In fact,

$$p_t' = p_{BY} \prod_{i=BY}^{t-1} \frac{1+gx_i}{1+g_i} = p_{BY} \prod_{i = BY}^{t-1} (1+gx_i') \tag{C-6}$$

C.2.2 Discounting and Present Values

Another major factor that makes price an awkward measure of value is that the value of money itself depends on when it is received or spent. If, for example, a venture capitalist can expect to get a 20%/year return on his investments, a million dollars <u>now</u> has the same value to him as 1.2 million dollars a year from now.

Given an appropriate value for the <u>discount rate</u>, the number corresponding to the rate of return in the above example, then the values of cash flows that occur at different times can be compared by <u>discounting</u> them to the same date (which can be called <u>the present</u>).

What date should be used as <u>the present</u>? Any date will do, so long as it is used consistently. In an attempt to reduce confusion, FINANCE.RPT uses the same date as is used for real prices - the base year.

What value should be used for the discount rate? In general, it should be that number, say k, which causes indifference between a cash flow of a million dollars at time t and a cash flow of (1+k) million dollars at time (t+1). Financial analysts are not in complete agreement as to how a company's financial parameters should be combined to produce a value: Some use the weighted average after-tax cost of capital, given by the following formula and recommended by the economists at JPL:

$$k = (1-\tau)\frac{\lambda-1}{\lambda} i + \frac{1}{\lambda} \rho \qquad \text{(C-7)}$$

where

k = The discount rate for a company.

τ = Marginal combined federal, state, and local income tax rate.

λ = Financial leverage, the ratio of total capital to equity capital.

i = Debt interest rate.

ρ = Required (or desired) rate of return on equity.

Others use the weighted average before-tax cost of capital. Still others use the rate of return on equity.

The present value of a stream of cash flows is the sum of the present values of the individual flows, and may be computed by the following equation:

$$\text{Present Value} = \sum_{t=-\infty}^{\infty} \frac{CF_t}{(1+k)^{t-BY}} \qquad \text{(C-8)}$$

where

CF_t = The cash flow at time t, expressed in nominal terms (i.e., year t dollars).

The present value of a stream of cash flows is the amount of money one would have to have at "the present" to have the same amount of value as is represented by the entire cash flow stream.

FINANCE.RPT uses equation (C-7) to compute the MSS-supplying company's discount rate. The MSS customer's discount rate, on the other hand, is an input - because the customer class for which a figure of merit is desired might not be a company.

C.2.3 The Required Revenue Approach

Regulatory bodies (such as public utility commissions) in certain industries try to set prices so as to be fair both to customers and to suppliers. They protect the suppliers by deciding what constitutes a "reasonable" rate of return on equity (i.e., "profit") and by approving price structures that are expected to produce revenues that will provide that amount of profit after expenses are met. They protect the customers by deciding which expenses are allowable and by attention to the details of the price structure.

Whether the industry being studied is regulated or not, this is a reasonable approach for determining normative prices. That is, considering a "reasonable profit" to be one of the costs, choose prices so that

$$\text{Present Value (Revenues)} = \text{Present Value (Costs)} \qquad \text{(C-9)}$$

It is important to note that this equation may also be interpreted as expressing the relationship between profit and price. That is, if the price is determined by market forces, rather than by fiat, equation (C-9) provides an implicit estimate of the resultant rate of return on equity - even if it is the price which is treated as the independent variable.

C.2.4 Pricing Strategy

The MSS-supplying company would like to choose a pricing strategy that will maximize its profit. Because sales volumes depend, at least to some extent, on the prices, selection of an optimal pricing strategy requires an understanding - or at least a model - of that dependence. No such model could be developed within the scope of the financial analysis task. Consequently, determination of an optimal pricing strategy was not feasible.

On the other hand, continuing to take the role of a regulatory body can lead to the requirement that all customers be charged the same price. If "the same" means "in real terms" (or, equivalently, "in constant dollars"), then the pricing strategy, by fiat, is given by the following equation:

$$P_t = P_{BY} \prod_{i=BY}^{t-1} (1+g_i) \tag{C-10}$$

$$= P_{BY}(1+g)^{t-BY} \qquad \text{if } g_t = g \text{, a constant} \tag{C-11}$$

where

P_t = The real levelized price in year t, expressed in nominal dollars per unit.

P_{BY} = The real levelized price, expressed in base year dollars per unit.

g_t = As before, the inflation rate in year t.

While it is highly recommended that this pricing policy be used, FINANCE.RPT does not require it; equation (C-1) is used, not equation (C-11), for both usage charge rates, CU_t, and customer charge rates, CC_t.

FINANCE.RPT allows any price versus time function. If real levelized pricing is desired, the usage charge escalation rates should all be equal to the inflation rate. If nominal levelized pricing is desired, the escalation rates should all be zero.

C.3 SUPPLIER'S COST

The supplier's cost in year t is given by equation (C-12):

$$COSTt = At + INTt + INSt + OTXt + OPRt + MNTt + TAXt \qquad \text{(C-12)}$$

where

COSTt = Total cost (excluding profit) in year t, expressed in M $(nominal) - that is, in millions of nominal dollars.

At = Amortization of capital assets, in M $(nominal).

INTt = Interest on corporate debt, in M $(nominal).

INSt = Insurance premiums, in M $(nominal).

OTXt = Property taxes, in M $(nominal).

OPRt = Operating expenses, in M $(nominal).

MNTt = Maintenance expenses, in M $(nominal).

TAXt = Combined federal, state, and local income taxes, in M $(nominal).

C.3.1 Amortization of Capital

The actual purchase costs of capital goods are not explicitly included in the cost equation (C-12). It is assumed that capital assets are purchased with funds obtained from equity investment and debt financing.

Revenues are not required to purchase capital goods, but they must cover equity and debt repayment, as well as return on equity and interest on debt, in addition to the costs of operating the system.

For FINANCE.RPT, annual amortization, At, is assumed to start in the first operating year and finish in the last operating year. The amount of amortization is calculated by dividing the book value of capital assets at the end of the preceding year by the number of years remaining. The book value is then reduced by the amount of amortization - but it may be increased by new investment. Thus,

$$At = \begin{cases} 0 & \text{if Year} < \text{Launch Year} \\ BVt_{-1}/(\text{LastOpYear} - \text{Year} + 1) & \text{otherwise} \\ 0 & \text{if Year} > \text{LastOpYear} \end{cases} \qquad \text{(C-13)}$$

where

BVt_{-1} = Book value at the end of the previous year, in M $(nominal).

LastOpYear = Last operating year.

Year = Current year.

The book value is calculated by

$$BVt = CumIt - CumAt \tag{C-14}$$

where

$CumIt$ = Cumulative investment, in M \$(nominal).

$CumAt$ = Cumulative amortization, in M \$(nominal).

The cumulative investment and amortization are given by

$$CumIt = CumIt_{-1} + Kt \tag{C-15}$$

$$CumAt = CumAt_{-1} + At \tag{C-16}$$

where

Kt = Annual investment, in M \$(nominal).

The annual investments are, in turn, calculated by inflating the capital investment requirements:

$$Kt = KSt\ (1+gKS)^{Year - BY} + KLt\ (1+gKL)^{Year - BY} + KFt\ (1+gKF)^{Year - BY} + KGt\ (1+gKG)^{Year - BY} \tag{C-17}$$

where

KSt, KLt, KFt, KGt = Annual investments, expressed in M \$(BaseYr).

gKS, gKL, gKF, gKG = Capital cost escalation rates.

BY = Base Year.

C.3.2 Interest on Debt

The amount of debt is assumed to be maintained at a constant fraction of the book value of the company's assets:

$$INTt = BVt\ i\ \frac{lambda - 1}{lambda} \tag{C-18}$$

where

i = Debt interest rate.

lambda = Financial leverage.

C.3.3 Insurance Premiums

Insurance premiums are modeled as a constant fraction of the book value of the company assets.

$$INSt = BVt\ \ beta2 \tag{C-19}$$

where

beta2 = Insurance rate.

C.3.4 Property Taxes

Property (or "Other than income") taxes are modeled as a constant fraction of the company's value on separate books kept for tax purposes.

$$OTXt = TVt\ beta1 \tag{C-20}$$

C.3.5. Operating Costs

Operating costs are assumed to be linearly dependent on the average traffic:

$$OPRt = p\ (1 + gOPR)^{Year\ -\ BY}\ Et\ 525960/10^6 \qquad \text{(C-23)}$$

where

p = Operating cost rate, in \$(base year)/call-minute.

$gOPR$ = Operating cost escalation rate.

Et = Average traffic, in Erlangs.

525960 = Number of call-minutes in an Erland-year.

10^6 = Conversion factor from \$ to M\$.

C.3.6. Maintenance Costs

Maintenance costs are assumed to increase with the replacement value of the cumulative capital investment.

$$MNTt = m\ RVt \qquad \text{(C-24)}$$

where

m = Annual maintenance cost fraction, in \$(nominal)/year per \$(nominal) of replacement cost.

RVt = Replacement cost of cumulative capital investment, in M\$(nominal).

where

TVt = Tax book value at the start of the year, in M $(nominal).

$beta1$ = Property tax rate.

The tax book value is calculated like the book value except that amortization is replaced by depreciation.

$$TVt = TVt_{-1} + Kt - Dt \tag{C-21}$$

where

Dt = Annual depreciation of capital assets, in M $(nominal).

Depreciation is the IRS-approved model for representing the exploitation of the value of a capital asset. Tax depreciation schedules are designed to meet political objectives (such as the encouragement of investment in capital goods) and may or may not be useful for amortization.

The currently approved model is called ACRS, for "Accelerated Capital Recovery System"; the relevant tables are reproduced on the spread sheet. The appropriate table to use for a particular capital investment depends upon its tax-life - which is usually significantly shorter than its expected useful life. FINANCE.RPT uses the 10-year taxlife table for all of the company's capital assets.

Annual depreciation is computed by equation (C-22).

$$Dt = \sum_{age=1}^{10} Kt_{-age} \text{ table(age; 10-year TaxLife)} \tag{C-22}$$

The replacement cost model omits removal of the value of decommissioned assets due to the presumption that no hardware is decommissioned until the end of the project:

$$RVt = RVt_{-1}\ (1+g) + Kt \tag{C-25}$$

where

g = General rate of inflation.

C.3.7 Income Taxes

The income tax model is simplified to the extent that the graduated tax table is represented by a single tax rate and that losses and credits are allowed to produce negative income taxes, rather than carry-forward and carry-back adjustments. While these simplifications could have a slight effect if the MSS-supplying company is a stand-alone financial entity, they accurately represent the impact of income taxes if the company is a subsidiary of a "parent".

$$TAXt = tau\ TIt - ITCt \tag{C-26}$$

where

tau = Combined federal, state, and local income tax rate.

TIt = Taxable income, in M $(nominal).

ITCt = Investment tax credit, in M $(nominal).

The MSS-supplying company's taxable income is given by

$$TIt = REVt - OPRt - MNTt - INSt - OTXt - INTt - Dt \qquad (C-27)$$

where

REVt = Annual revenues, in M $(nominal).

The investment tax credit allowed is a fraction of the annual investment.

$$ITCt = beta3\ Kt \qquad (C-28)$$

where

beta3 = Investment tax credit rate.

C.4 SUPPLIER'S REQUIRED REVENUES

In addition to providing enough money to pay the expenses developed in Section C.3, the revenues must also provide a reasonable return to the equity investors (stockholders). The part of the book value of the company which is not debt must be equity. Consequently, the desired return on equity is given by

$$GoalNPt = rho\ BVt_{-1}/lambda \qquad (C-29)$$

where

GoalNPt = Net Profit that would be obtained in year t if the equity investors were to receive the specified rate of return (rho), in M $(nominal).

rho = Specified rate of return on equity.

Thus, the required revenue if the investors were to be satisfied each year is given by adding equations (C-12) and (C-29):

$$\text{ReqREVt} = \text{COSTt} + \text{GoalNPt} \tag{C-30}$$

where

ReqREVt = Required revenue in year t, expressed in M $(nominal).

C.5 SUPPLIER'S REVENUES

It is assumed in FINANCE.RPT that all customers are offered the same prices, but that there are two components to their monthly bills: a subscription charge and a usage charge. It is also assumed that prices may change from year to year, as specified by the analyst using the program. Thus,

$$\text{REVt} = \text{REVCUt} + \text{REVCCt} \tag{C-31}$$

where

REVt = Annual revenue, in M $(nominal).

REVCUt = Component of annual revenue due to usage charges, in M $(nominal).

REVCCt = Component of annual revenue due to customer charges, in M $(nominal).

C.5.1 Usage Revenues, REVCUt

Usage revenues are simply the product of the usage charge rate and the average traffic:

$$\text{REVCUt} \doteq \begin{cases} \text{CUt Et } 525960/10^6 & \text{if Year} \leq \text{LastOpYear} \\ 0 & \text{otherwise} \end{cases} \tag{C-32}$$

where

CUt = Usage charge rate in year t, in \$(nominal)/Call-Minute.

Et = Average traffic in year t, in Erlangs.

525960 = Number of Call-Minutes in an Erlang-Year.

10^6 = Conversion factor from \$ to M \$.

The time-varying usage charge rate is calculated in FINANCE.RPT from the analyst's input escalation rates and from the initial value determined by the program.

$$CUt = \begin{cases} CUold\ (1+gCUt)^{Year\ -\ BY} & \text{if Year = FCY} \\ CUt_{-1}\ (1+gCUt) & \text{otherwise} \end{cases} \qquad (C\text{-}33)$$

where

$CUold$ = Latest iterative estimate of the initial usage charge rate, in \$(Base Year)/Call-Minute.

$gCUt$ = Input usage charge escalation rate.

FCY = First calendar year in the analysis.

Average traffic is modeled on the assumption that latent demand is greatly in excess of system capacity, so that usage and customers increase exponentially until the system is saturated. The model is specified by the growth rate in the exponential phase and by the conditions at and timing of saturation.

$$Et = \begin{cases} 0 & \text{if } t \le 0 \\ Esat\ (1+rg)^{t\ -\ TS} & \text{if } 0 < t \le TS \\ Esat & \text{if } TS \le t \end{cases} \qquad (C\text{-}34)$$

where

> Esat = Traffic at saturation, in Erlangs.
>
> rg = Sales growth rate during the exponential growth period.
>
> TS = Number of years after launch to achieve saturation.
>
> t = Number of years after launch.

$$t = Year - LaunchYear \tag{C-35}$$

where

> LaunchYear = First operating year.

C.5.2 Subscription Revenues

Customer charge (or subscription) revenues are the product of the customer charge rate and the number of customers.

$$REVCCt = \begin{cases} CCt\ Nt\ 12/10^6 & \text{if Year} \leq \text{LastOpYear} \\ 0 & \text{otherwise} \end{cases} \tag{C-36}$$

where

> CCt = Monthly customer charge, in \$(nominal)/Customer-Month.
>
> Nt = Average number of customers.
>
> 12 = Conversion factor from months to years.
>
> 10^6 = Conversion factor from \$ to M \$.

The time-varying customer charge rate model is similar to that for the usage charge rate.

$$CCt = \begin{cases} CC\ (1+gCCt)^{Year\ -\ BY} & \text{if Year = FCY} \\ CCt_{-1}\ (1+gCCt) & \text{otherwise} \end{cases} \tag{C-37}$$

where

CC = Input initial customer charge rate, in Base Year$/Customer-Month.

$gCCt$ = Customer charge escalation rate.

For simplicity, FINANCE.RPT assumes that the shape of the customer charge rate as a function of time is the same as that for the usage charge.

$$gCCt = gCUt \tag{C-38}$$

The number of customers is assumed to follow the same pattern as the traffic.

$$Nt = \begin{cases} 0 & \text{if } t \leq 0 \\ Nsat\ (1+rg)^{t - TS} & \text{if } 0 < t \leq TS \\ Nsat & \text{if } TS \leq t \end{cases} \tag{C-39}$$

where

$Nsat$ = Number of customers at saturation.

As a consequence of the similarity of equations (C-34) and (C-39), the average usage per customer is constant, though this statement would not necessarily stay true if the models for Et and/or Nt were changed.

C.6 USER CHARGES

The required revenue approach to determining normative prices states that prices are to be chosen so that

$$REVpv = ReqREVpv, \tag{C-40}$$

which is a restatement of equation (C-9), and in which

REVpv = Present value, as obtained from equation (C-8), of the annual revenues REVt, given by equation (C-31).

ReqREVpv = Present value, from equation (C-8), of a stream of revenues that would provide the specified return to the equity investors, given by equation (C-30).

As a result of the modeling described earlier in this section, equation (C-40) can be thought of as an equation in one unknown, CUold, which can be solved by one means or another. FINANCE.RPT does so by the following iterative procedure:

$$\text{Delta} = (\text{ReqREVpv} - \text{REVpv})/\text{PresentValue}(\text{REVCUt}) \tag{C-41}$$

where

Delta = A measure of the amount by which the current value of CUold fails to satisfy equation (C-40).

$$\text{CUnew} = \text{CUold}\ (1 + 2\ \text{Delta}) \tag{C-42}$$

where

CUnew = New estimate of the initial usage charge rate.

```
If Abs(Delta) < 0.001
        Set "Done" to TRUE and terminate iteration
Otherwise                                                    (C-43)
        Set CUold = CUnew and continue iteration
Endif
```

It should be noted that an attempt to solve for a year-by-year price, CUt, that solves REVt = ReqREVt could lead to very peculiar results, because there may be years in which the revenues are zero or negative for <u>any</u> price (e.g.,

prior to the first operating year), yet the required revenues for some of those years are not zero. The present value operation allows the company to move the cash flows among the years available, so that thé required revenue condition can be meaningfully met.

It should also be noted that the solution of equation (C-40) could have been for CC, with CUold an input, instead of vice versa. The choice that was made was arbitrary.

C.7 FOM - ANALYSIS OF CUSTOMER FINANCES

The objective of FINANCE.RPT is to provide a means for comparing alternative designs for MSS systems. Is it better, for example, to develop a very large space antenna so that MSS-customer equipment can be simple and inexpensive? Or should development concentrate on medium-gain customer hardware so that usage costs will be low?

The ideal figure of merit (FOM) would provide a measure of the net societal benefits offered by the alternatives. Such a measure would include an assessment of the benefits to future generations of building large space structures sooner, rather than later. These benefits may be quite large, and are appropriately included when making project decisions. They are also very difficult to estimate, and are <u>not</u> included in the FOM provided by FINANCE.RPT.

The interests of investors, both in the MSS-supplying companies and in the companies with which they compete, are assumed to be taken care of by the use

of the required revenue approach. Validity of this assumption requires that the value of the required rate of return on equity accurately corresponds to the perceived risk of investment in an MSS-supplier.

The interests of potential customers that choose not to subscribe are assumed to be reflected by their behavior. That is, they are assumed to weigh their opportunity costs and other externalities, such as the quality of service, when they make their subscription decisions.

If the demand function for potential customers were known, the appropriate FOM would include an accounting for opportunity costs and a joint optimization of supplier's pricing policies and customers' subscription decisions. Calculation of the FOM would be a straightforward, interesting, tough optimization problem. A description of how demands (i.e., sales) vary with time would be part of the solution to that problem. Development of a model of the demand function, however, would require a study effort an order of magnitude or two larger than was available for the rest of this study.

In the absence of a known demand function, the variation of sales with time has been assumed. With this assumption, the opportunity costs (the costs of not being able to place desired calls due to not being a MSS subscriber), the costs of calls placed on non-MSS systems, and the costs of subscribing to MSS sooner or later than would be optimal, are the same for all MSS system designs.

C.7.1 The Figure of Merit

With the qualifications discussed in the previous section, a satisfactory figure of merit for comparing alternative system designs can be obtained by averaging the MSS-related costs incurred by all MSS customers. These costs contain three components: usage costs, subscription costs, and equipment costs. The resultant measure is appropriately called a "figure of merit", rather than a "total users` cost", because opportunity costs are not included, the optimization problem has been assumed away, disparate users` costs are averaged, and costs that occur at different times are combined by discounting and real levelization.

$$FOM = \sum_{Year} \frac{NUt}{Nsat} \, COSTyrt/(1+u)^{Year - BY} \tag{C-44}$$

where

FOM = Figure of merit for comparing system designs (smaller is better), in discounted BaseYear$/year per customer.

NUt = Number of new customers in year t.

Nsat = Total number of new customers who subscribe to the service.

COSTyrt = Real levelized annual cost for a customer who first subscribes in year t, expressed in $(nominal)/year.

u = Representative user`s discount rate, in fraction/year.

BY = Base Year.

Year = Year at the start of which the new customer subscribes.

The number of new customers is obtained quite simply from the customer model:

$$NUt = Nt - Nt_{-1} \tag{C-45}$$

C.7.2 Customer Cost Components

The real levelized annual cost for a new user is computed from the monthly cost, which is the sum of monthly usage costs, subscription costs, and equipment costs:

$$COSTyrt = 12\ COSTmot \tag{C-46}$$

$$COSTmot = CUmot + CCmot + KUmot \tag{C-47}$$

where

COSTmot = Real levelized annual cost for a customer who first subscribes at the beginning of year t, expressed in \$(nominal)/month.

CUmot = Real levelized equivalent of the annual usage charges for a customer who first subscribes at the beginning of year t, expressed in \$(nominal)/month.

CCmot = Real levelized equivalent of the annual subscription charges for a customer who first subscribes at the beginning of year t, expressed in \$(nominal)/month.

KUmot = Real levelized equivalent annual cost, expressed in \$(nominal)/month, of the costs of purchasing, operating, maintaining, and replacing MSS equipment for a customer who first subscribes at the beginning of year t.

Although the cost of the MSS-supplying project is calculated as though it has a limited lifetime, customers presumably will purchase service from successors, as well. Whether actual successor systems will offer better prices than the system under study, however, should not affect the assessment of a particular design. Hence, it is assumed for customer cost estimation that the MSS system is replaced by replicas of itself as necessary. It is also assumed that escalation and discount rates continue into the indefinite future without change.

The levelized cash flow rate associated with a present value is given by

$$CF = PV\ crf(dr, life) \tag{C-48}$$

where

CF = Uniform periodic payment in \$/(time period) corresponding to PV, with interest rate dr, for life time periods.

PV = Present value of a cash flow stream of CF for each of life time periods, with discount rate dr.

dr = Discount or compound interest rate, assumed to be constant throughout life time periods.

life = Number of time periods for which the cash flow stream CF is continued to produce a present value of PV when discounted at rate dr.

crf( ) = Capital recovery factor.

If dr is the real discount rate, CF is the real levelization of PV; if dr is the nominal discount rate, CF is the nominal levelizaton of PV.

The capital recovery factor may be computed from

$$crf(dr, life) = \begin{cases} dr/[1 - (1+dr)^{-life}] & \text{if } dr \neq 0 \\ 1/life & \text{if } dr = 0 \end{cases} \tag{C-49}$$

Indefinitely continued subscription corresponds to an infinite life, with the result that the capital recovery factor is equal to the discount rate. Hence,

$$CUmot = CUpvt\ (u-g)/12 \tag{C-50}$$

$$CCmot = CCpvt\ (u-g)/12 \tag{C-51}$$

where

CUpvt = Present value of all future usage charges for a customer who first subscribes at the beginning of year t, expressed in \$(Year t).

CCpvt = Present value of all future subscription charges for a customer who first subscribes at the beginning of year t, expressed in \$(Year t).

u = Users' nominal discount rate, in fraction/year.

g = General rate of inflation, in fraction/year.

The present values are computed by applying equation (C-8) to the annual costs.

The annual costs are computed as follows:

$$ICUyrt = 12\ ICUmot \tag{C-52}$$

$$ICCyrt = 12\ ICCmot \tag{C-53}$$

$$ICUmot = CMmot\ CUt \tag{C-54}$$

$$ICCmot = CCt \tag{C-55}$$

$$CMmot = 43830\ Et/Nt \tag{C-56}$$

where

ICUyrt = Annual usage charges during year t, in \$(nominal)/year.

ICUmot = Same as ICUyrt, but in \$(nominal)/month.

ICCyrt = Annual subscription charges during year t, in \$(nominal)/year.

ICCmot = Same as ICCyrt, in \$(nominal)/month.

CMmot = Average number of Call-Minutes/month per customer.

43830 = Number of Call-Minutes in an Erlang-Month.

Et = Traffic, in Erlangs.

Nt = Number of customers.

Similarly, the real levelized equivalent annual cost of customer equipment can be calculated from the present value of the rather irregular stream of equipment-related costs.

$$KUmot = KUpvt\ (u-gKU)/12 \qquad \text{(C-57)}$$

where

KUpvt = Present value of all present and future equipment-related costs for a customer who first subscribes at the beginning of year t, in \$(Year t).

gKU = Customer's equipment escalation rate, in fraction/year.

$$KUpvt = CCMU \cdot KUt \qquad \text{(C-58)}$$

where

CCMU = Customer's capital cost multiplier, the ratio of the present value of all equipment-related costs to the purchase cost.

KUt = Customer's equipment cost, in \$(nominal) per customer.

$$KUt = KU\ (1+gKU)^{Year\ -\ BY} \qquad \text{(C-59)}$$

where

KU = Customer's equipment cost in \$(Base Year).

The customer's capital cost multiplier plays the same role as the analysis of the suppliers' finances with regard to the impact of capital investment. In the suppliers' case, however, almost all of the costs are due to capital, so a relatively detailed model is necessary. In the customer's case, a large part of the total cost results from the charges, so a simpler, closed-form model of the impact of capital costs should suffice.

The following model is based on a derivation contained in JPL Document 5040-29 [Ref. 1].*

$$CCMU = \left(\frac{1 - \dfrac{tauU}{KUlife\ CRFU} - beta3U}{1 - tauU} + \frac{beta1U + beta2U + mU}{CRFU} \right) ERMU \qquad (C\text{-}60)$$

where

tauU = Customer's marginal income tax rate.

KUlife = Expected useful lifetime of customer equipment, in years. ("Straight Line" depreciation is assumed.)

CRFU = Customer's capital recovery factor, evaluated by equation (C-49), using a discount rate of u and an amortization period of KUlife.

beta3U = Customer's investment tax credit rate.

beta1U = Customer's property tax rate.

beta2U = Customer's insurance rate.

mU = Customer's annual maintenance cost fraction.

ERMU = Customer's equipment replacement multiplier.

The customer's equipment replacement multiplier, ERMU, accounts for the fact that the equipment must be replaced every KUlife years. Meanwhile, the replacement cost escalates at a rate of gKU, but the present value of these replacements is diminished by discounting at the customer's discount rate, u. As a result of these factors:

* Reference 1: "The Cost of Energy from Utility-Owned Solar Electric Systems: A Required Revenue Methodology for ERDA/EPRI Evaluations", J. W. Doane, et al., JPL 5040-29 and ERDA/JPL-1012-76/3, Jet Propulsion Laboratory, Pasadena, CA, June, 1976.

$$\text{ERMU} = 1/\left(1 - \left(\frac{1+\text{gKU}}{1+\text{u}}\right)^{\text{KUlife}}\right) \qquad \text{(C-61)}$$

C.7.3 Costs for New Users

It has been shown [Ref. 2]* that the optimal time for a potential customer to subscribe to the service is when the real levelized cost falls below that of the status quo. (In this case, the status quo cost should include the opportunity cost.) This cost has already been developed above as COSTyrt, but expressed in terms of nominal dollars; FINANCE.RPT also shows those costs in Base Year dollars and as present values of the real levelized cost streams.

* Reference 2: "A Decision Rule for the Installation of a Solar Electric System", R. G. Chamberlain and L. H. Orren, Proceedings of the IASTED Energy Symposia, San Francisco, May 1981, ACTA Press. The paper was also published as JPL Document 900-990 No. 9, July 1981, and was also presented at the Western Economic Association meeting in July 1981.

APPENDIX D

PAYLOAD WEIGHT MODEL

D.0 INTRODUCTION

Estimation of the payload weight is an important step in the design of a mobile satellite system. The estimated payload weight can be used to size the system and estimate the resulting capacity. The payload weight of a mobile satellite system consists primarily of the antenna, the UHF or L-band feed assembly, the backhaul subsystem, and the rest of the transponder. The weight of the feed assembly depends on the design of the feed, i.e., single or overlapping feed. For this reason, two models will be presented for the two different feed designs.

D.1 ANTENNA WEIGHT

The weight of the UHF or L-band antenna, which includes the reflector and its supporting boom, accounts for a major portion of the payload weight. For a given antenna diameter, the weight varies as a function of many parameters including the surface accuracy (σ/λ), focal-length-to-diameter ratio (F/D), antenna type (wrap-rib or hoop-column), antenna configuration (offset or symmetric), and the design of the boom. For the MSAT-2 baseline, the antenna is a Lockheed wrap-rib deployable offset antenna with an F/D = 1.0 and σ/λ = 1/60. The design of the boom affects the structural stiffness and the stowed dimensions of the antenna, as well as the weight of the antenna. It is necessary to recognize that the antenna weight could vary over a wide range for a given diameter depending on the boom design, the resulting stiffness, and the stowed volume.

The estimated weight of the reflector, for various sizes and surface accurancies, is tabulated in Table D-1 for both the UHF and L-band frequencies. The data is obtained from [1]. The L-band antenna data is included for the design of an alternative system. The UHF antenna is the baseline antenna.

The weight of the mast for various antenna sizes is provided in Table D-2. Since the mast weight is very sensitive to its design, two different designs have been included in the table. One design utilizes a 6-foot bay with an aspect ratio of unity, and the other is based on a 12-foot bay with an aspect ratio of 2. The 6-foot design is structurally not as stiff as the 12-foot design and weighs a little bit more for the same antenna size. The advantage, however, is that it occupies less volume in the stowed configuration. The aspect ratio is the ratio of the bay length to the bay width. An illustration of the bay length and bay width is provided in Figure D-1. The stowed dimensions of a wrap-rib deployable antenna are shown in Figure D-2. The data in Table D-2 is based on [1].

Table D-1.

Estimated Reflector Weights for a Wrap-Rib Deployable Antenna

Operating at UHF and L-Band Frequencies

	UHF						L-BAND					
Reflector Diameter, m	15	20	30	15	20	30	8	20	30	8	20	30
Surface Accuracy (σ/λ)	1/30	1/30	1/30	1/60	1/60	1/60	1/30	1/30	1/30	1/60	1/60	1/60
Number of Ribs	12	14	18	18	20	24	12	18	22	16	26	32
Reflector Weight, kg	58	72	122	72	90	153	47	84	142	52	108	195

Table D-2.

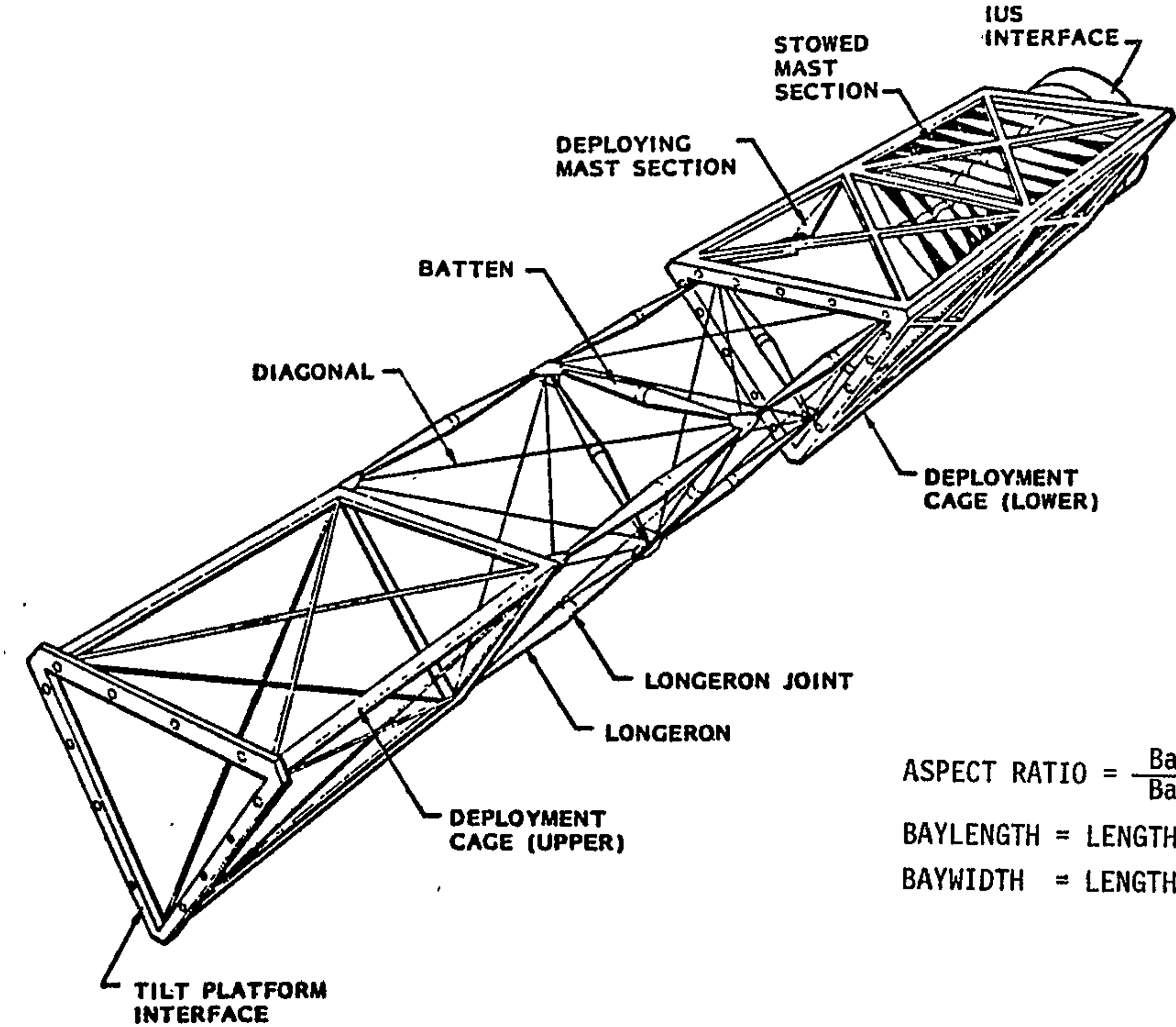
Estimated Mast Weight for a Wrap-Rib Deployable

Offset-Fed Antenna(1)

Reflector Diameter, m	8	15	20	30	8	15	20
Mast Design							
Bay Width, ft.	6	6	6	6	6	6	6
Bay Length, ft.	12	12	12	12	6	6	6
Aspect Ratio	2	2	2	2	1	1	1
Antenna Stowed Dimensions							
Antenna Stowed Diameter, ft.	13.8	13.8	13.8	13.8	9.2	9.2	9.2
Mast Stowed Length, ft.	1.3	1.7	1.8	2.9	1.9(1)	2.4(1)	2.7
Reflector Stowed Length, ft.	1.1	1.1	1.1	1.2	1.1	1.1	1.1
Antenna Stowed Length, ft.	14.4	14.7	14.9	16.1	9.0	9.5	9.7
Antenna Natural Frequency, Hz	18.6	5.5	3.2	1.5	-	-	2.7
Mast Weight, kg	33	55	68	106	44(2)	73(2)	90

Notes:

(1) The estimated weight in [1] was based on F/D = 1.2.
(2) Scaled from the 20-m case.

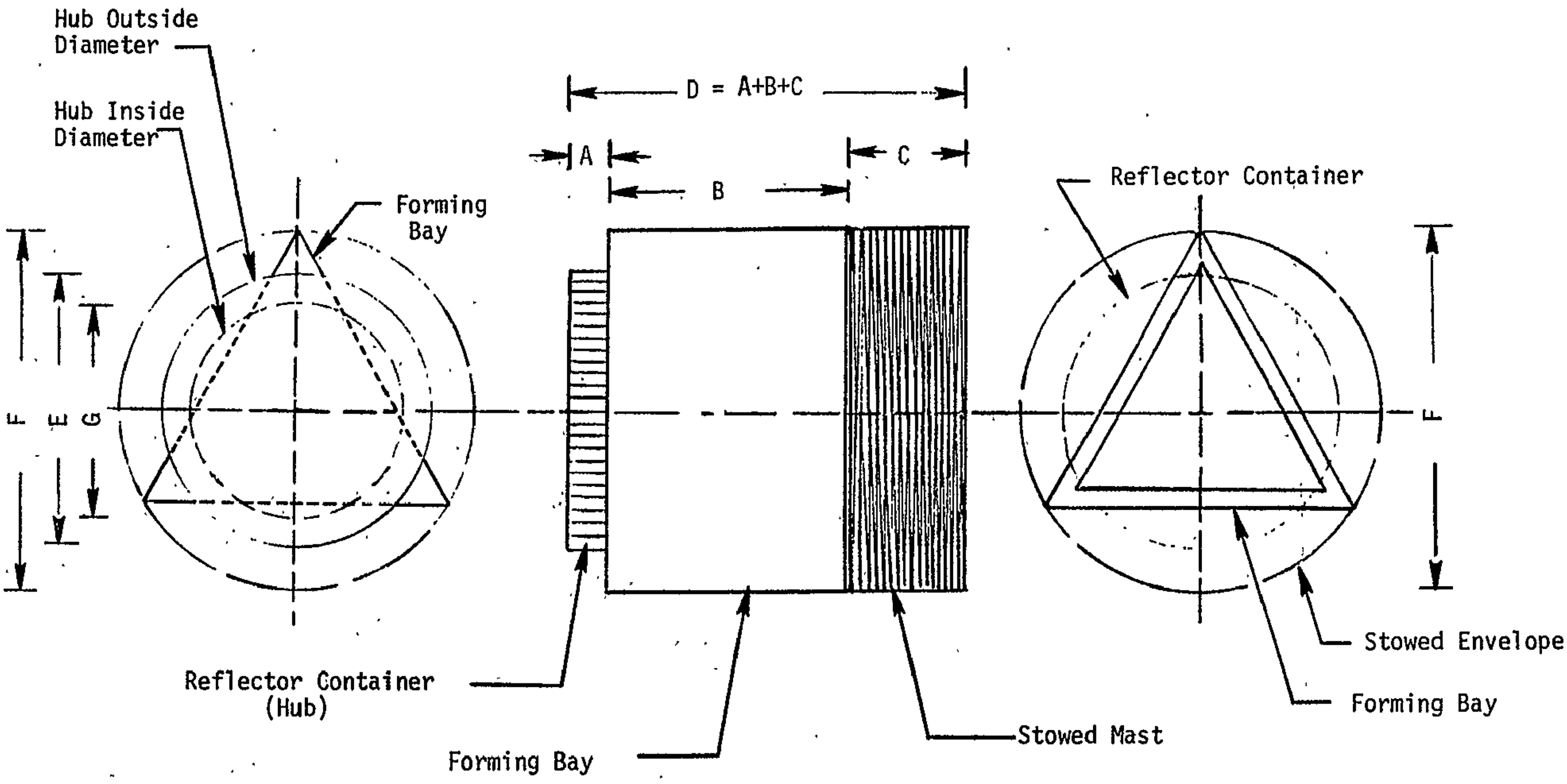


$$\text{ASPECT RATIO} = \frac{\text{Bay Length}}{\text{Bay Width}}$$

BAYLENGTH = LENGTH OF LONGERON

BAYWIDTH = LENGTH OF BATTEN

Figure D-1. Antenna Mast



Legend

A = Hub Height
B = Bay Length
C = Stowed Mast Length
D = Stowed Antenna Length
E = Hub Outside Diameter
F = Stowed Diameter
G = Hub Inside Diameter

Figure D-2. The Stowed Configuration of a Wrap-Rib Antenna

The total antenna weight, which includes the weight of the reflector, its supporting mast, and deployment mechanism, is estimated in Table D-3 for various combinations of antenna diameter, surface accuracy, and aspect ratio. The maximum weight, which includes a 20% mark up for contingency, is shown in the Table and plotted in Figures D-3 and D-4 for the UHF and L-band antennas. The weight estimates are derived from [1].

D.2 Antenna Feed Assembly Weight

The antenna feed assembly is another significant contributor to the total payload weight. The weight of the antenna feed assembly depends on the feed design as well as the operating frequency. For convenience, the UHF antenna feed assembly is discussed first. The feed assembly weight for the L-band system will be addressed later.

A block diagram of a mobile satellite transponder is shown in Figure D-5 for the nonoverlapping feed design and in Figure D-6 for the overlapping feed design. A detailed description of the feed assembly can be found in Chapter 2 and in [2]. The components of the feed assembly for a single feed design are the radiating elements, cables, supporting structures, and RF electronics, which include high power amplifiers (HPA's), low noise amplifiers (LNA's), and diplexers. In the case of an overlapping feed design, the feed assembly also requires a beamforming network (BFN), which includes a number of combiners and dividers. The block diagrams shown in both figures are for a satellite with 14 beams, which is not the MSAT-2 baseline design. These figures are for illustration only.

Table D-3.

Estimated Antenna Weights For A Wrap-Rib Deployable
Offset-Fed Antenna Operating At UHF and L-Band

Mast Design	Reflector σ/λ	Reflector Size m	UHF Antenna Weight, kg				L-Band Antenna Weight, kg			
			Reflector Weight	Mast Weight	Total Ant. Weight	Max. Ant Weight(3)	Reflector Weight	Mast Weight	Tot. Ant. Weight	Max. Ant. Weight(3)
6-ft Bay Design	1/30	8	40(1)	44	84	101	47	44	91	109
		15	58	73	131	157	68(2)	73	141	169
		20	72	90	162	194	84	90	174	209
		25	-	-	204(5)	245(5)	-	-	217(5)	260(5)
		30	122	140(4)	262	314	142	140(4)	282	338
	1/60	8	43(1)	44	87	104	52	44	96	115
		15	72	73	145(5)	174(5)	86	73	159(5)	191(5)
		20	90	90	180	216	108	90	198	238
		25	-	-	225(5)	270(5)	-	-	250(5)	300(5)
		30	153	140(4)	293	352	195	140(4)	335	402
2-ft Bay Design	1/30	8	40(1)	33	73	88	47	33	80	96
		15	58	55	113	136	68(2)	55	123	148
		20	72	68	140	168	84	68	152	182
		25	-	-	175(5)	210(5)	-	-	188(5)	225(5)
		30	122	106	228	274	142	106	248	298
	1/60	8	43(1)	33	76	91	52	33	85	102
		15	72	55	127	152	86(2)	55	141	169
		20	90	68	158	190	108	68	176	211
		25	-	-	196(5)	235(5)	-	-	225(5)	270(5)
		30	153	106	259	311	195	106	301	361

Notes:

(1) Scaled from L-band data. (2) Scaled from UHF data. (3) Including 20% for contingency.
(4) Scaled from 12-ft bay design data. (5) Scaled from 20-m and 30-m data. See Figures D-1 and D-2.

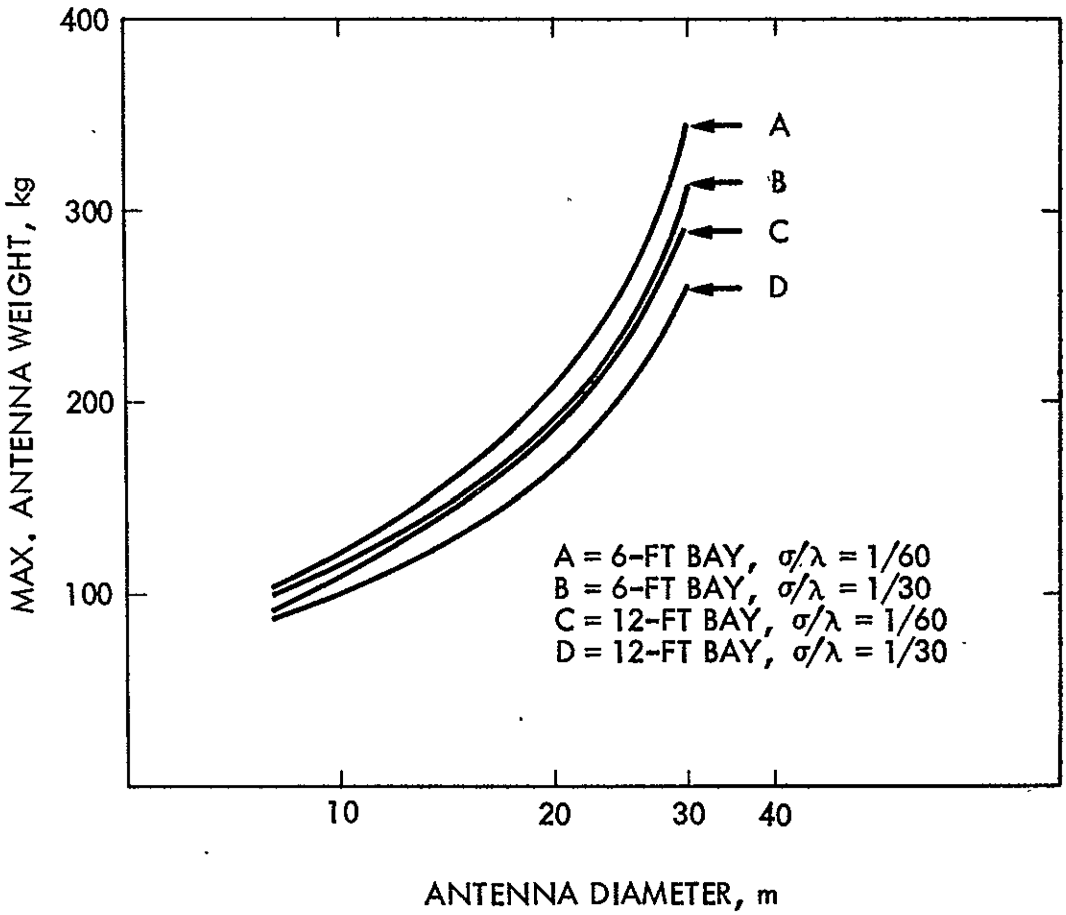


Figure D-3. Estimate Maximum Weight of a Wrap-Rib Deployable Offset-Fed Antenna Operating at UHF With a Fixed F/D of 1.2

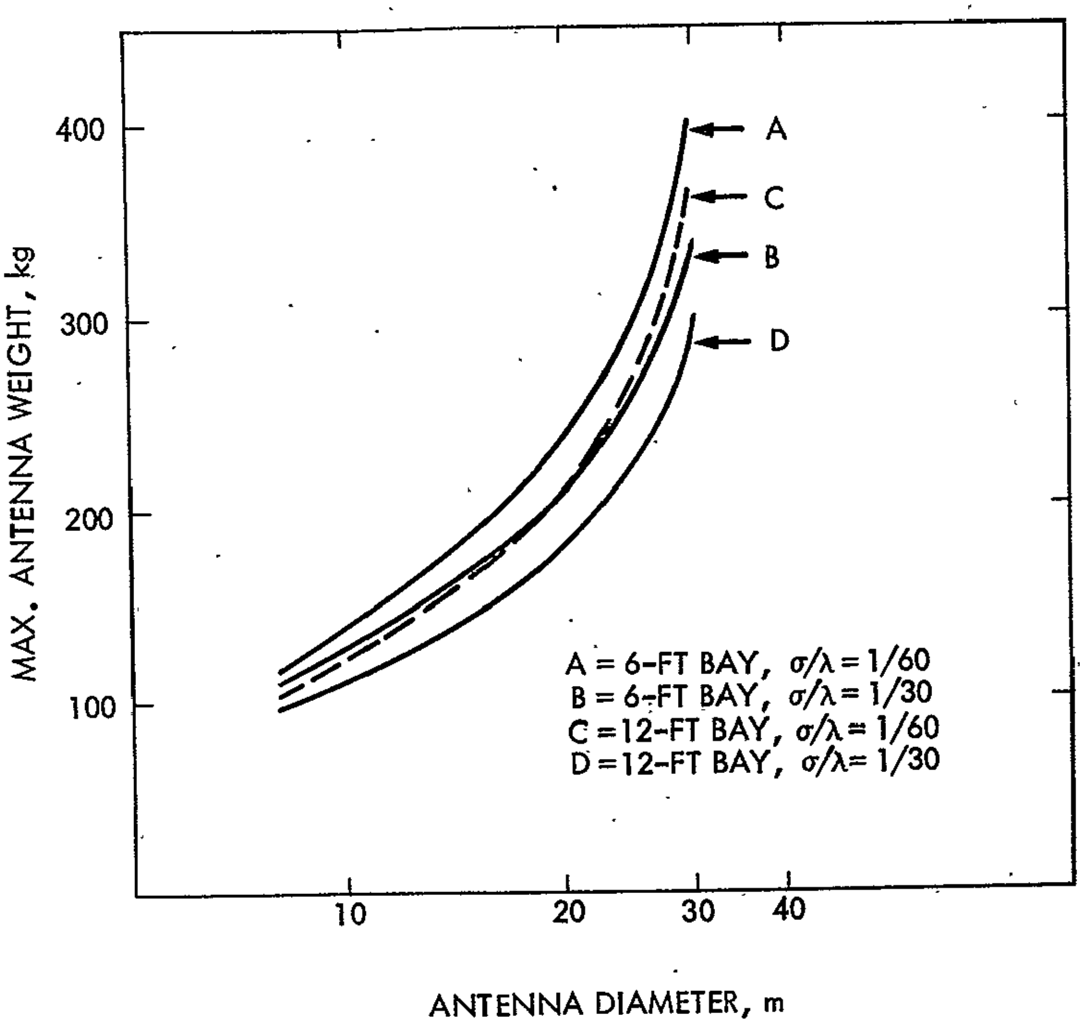
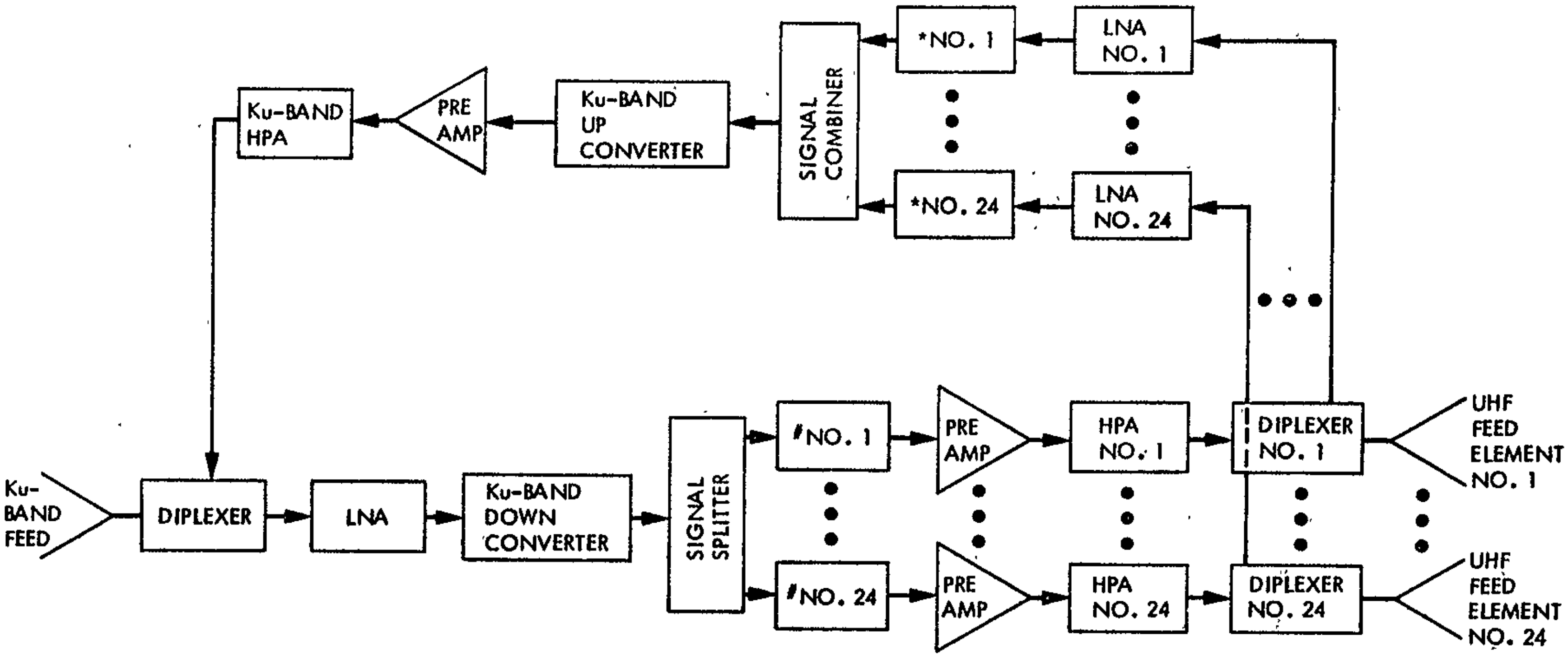


Figure D-4. Estimated Maximum Weight of a Wrap-Rib Deployable Offset-Fed Antenna Operating at L-Band With a Fixed F/D of 1.2



LEGEND

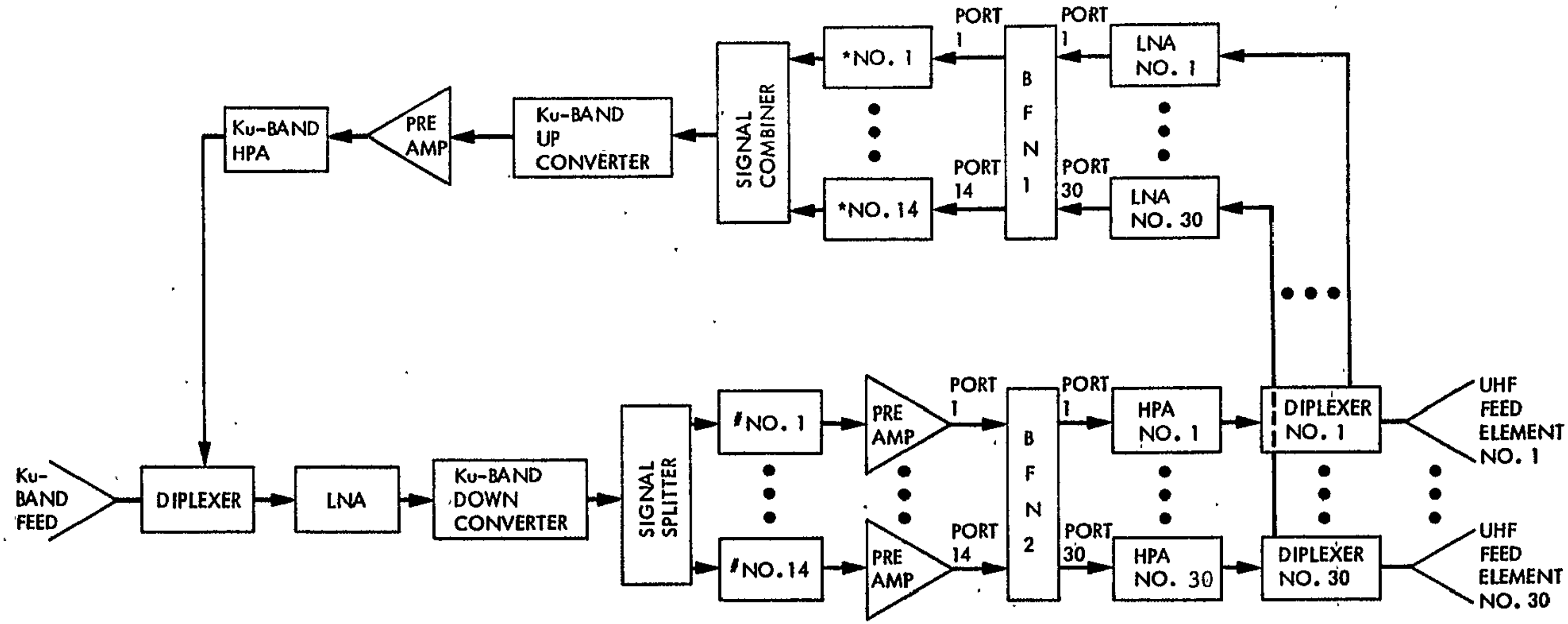
* UPLINK UHF RECEIVER/FREQUENCY TRANSLATOR

\# DOWNLINK RECEIVER/FREQUENCY TRANSLATOR

Figure D-5.

Transponder Block Diagram
Non-overlapping Feeds
Single Ku-Band Backhaul Beam

(For Illustration Only, 24-Beam Case)



LEGEND

BFN = BEAM FORMING NETWORK

* UPLINK UHF RECEIVER/FREQUENCY TRANSLATOR

\# DOWNLINK RECEIVER/FREQUENCY TRANSLATOR

Figure D-6.

Transponder Block Diagram
Overlapping Feeds
Single Ku-Band Backhaul Beam

(For Illustration only, 14-Beams Case)

The feed-assembly weight is strongly tied to the total number of feed elements in the feed as well as the number of beams. For a feed assembly using one-element feed design, each beam has one element and the total number of elements is equal to the number of beams. The weight of the feed assembly can thus be approximated as a function of the number of beams. For the overlapping feed design, there is no simple relationship between the number of beams, the number elements per beam, and the total number of elements. This is because part of the elements of a particular beam are also used to form other beams. The total number of elements is, therefore, less than the product of the number of beams and the number of elements per beam. The block diagram in Figure D-6 shows a total of 30 elements for 14 beams. A 4-element feed design for a 14-beam system would have such a transponder. In general, the total number of elements must be determined on an individual basis for the overlapping feed design; the feed assembly weight, thus, necessarily depends on both the number of beams and the number of feed elements.

Based on the above discussion, the feed-assembly weight for the UHF system is estimated by the following model:

$$W_{feed} = \begin{cases} 10.69\ N_B\ \text{[kg]} & \text{For single-element feed designs.} \\ 1.38\ N_B + 9.49\ N_E\ \text{[kg]} & \text{For overlapping feed designs.} \end{cases}$$

where N_B denotes the number of multiple beams, N_E the number of feed elements, and W_{feed} is the weight of the feed assembly. For a single-element feed design, $N_B = N_E$.

The above model is based on data obtained from [2], and estimates obtained from satellite manufacturers. The model includes some redundancy for the RF electronics and assumes that the output level of the power amplifiers is approximately 15 to 30 watts.

The above weight model is for a UHF feed assembly. The weight of some of the components of the feed assembly may be different for L-band. For example, the radiating elements are expected to be lighter. On the other hand, the weight of the power amplifier may be heavier because a higher output power may be required in order to compensate, for example, for the increased space loss. For the range of antenna sizes considered, the net difference in weight between the UHF and the L-band feed assembly is approximately 3.3 N_B for the single-element feed design, and 3.3 N_E for the overlapping feed design.

D.3 TRANSCEIVER WEIGHT

The transceiver includes all components of the transponder, excluding the feed assembly, the reflectors and the Ku-band TWT. Its weight (W_{TR}) is related to the number of beams and is approximated by

$$W_{TR} = 0.2\ N_B + 12.8\ [\mathrm{kg}]$$

The above equation includes the weight of power conditioner, oscillator, etc.

D.4 KU-BAND REFLECTOR AND KU-BAND TWT WEIGHTS

The weight of the Ku-band reflector, which is 5 m in diameter, is about 3.6 kg, and that of the Ku-band TWT, including a 100% redundancy, is 4.09 kg.

D.5 TOTAL PAYLOAD WEIGHT

The total payload weight is the sum of the individual component weights. Denoting the total payload weight by W_T, the following is the payload weight model for the UHF system:

$$W_T = W_{ANT} + 10.9\ N_B + 20.5\ [\mathrm{kg}]$$

for the single-feed design, and

$$W_T = W_{ANT} + 1.6\ N_B + 9.5\ N_E + 20.5\ [kg]$$

for the overlapping feed design. In the above equations, W_{ANT} is the weight of the UHF antenna.

For the L-band system, the model is

$$W_T = W_{ANT} + 7.6\ N_B + 20.5\ [kg]$$

for the single-element feed design, where W_{ANT} is the weight of the L-band antenna.

REFERENCES

[1] Final Report for Antenna Technology, LMSC-D971808, Lockheed Missiles and Space Company, Inc., October 12, 1984.

[2] Land Mobile Satellite Service (LMSS): A Conceptual System Design and Identification of the Critical Technologies, Part II: Technical Report, Edited by Firouz Naderi, JPL Publication 82-19, February 15, 1982.

APPENDIX E

OVERALL C/I CALCULATION

E.0 INTRODUCTION

The interference situation for the second-generation mobile satellite system is very complex. The system, as currently conceived, consists of two satellites using multiple UHF beams and a single backhaul beam. To increase the number of satellite channels, frequency reuse is currently planned for the UHF beams. A combination of the use of two satellites, multiple beams with frequency reuse, the multipath fading, and the broad beamwidth of the mobile antenna, makes the system very susceptible to cochannel interference. Interference is particularly severe for mobile-to-mobile communications. For fixed-station-to-mobile and mobile-to-fixed-station communications, the interference is less severe. The purpose of this Appendix is to analyze the interference situation and to calculate the overall C/I for various modes of communications.

E.1 INTERFERENCE ANALYSIS FOR MOBILE-TO-MOBILE COMMUNICATION

In a mobile-to-mobile communication, the mobile receiver suffers both cochannel and adjacent channel interference from many sources: turnaround uplink interference, intermodulation products, interbeam interference, and intersatellite interference. A typical interference scenario is shown in Figure E-1. As depicted, the desired signal is transmitted from a mobile user to a satellite, which in turn retransmits, after proper amplification, the signal to the intended user. In the uplink transmission, cochannel and adjacent channel interference exist due to transmissions by other users. In theory, both cochannel and adjacent channel interference degrade the link performance and, hence, both should be accounted for. For a rough approximation, however, adjacent channel interference can be assumed to have negligible effects due to the use of spectrally

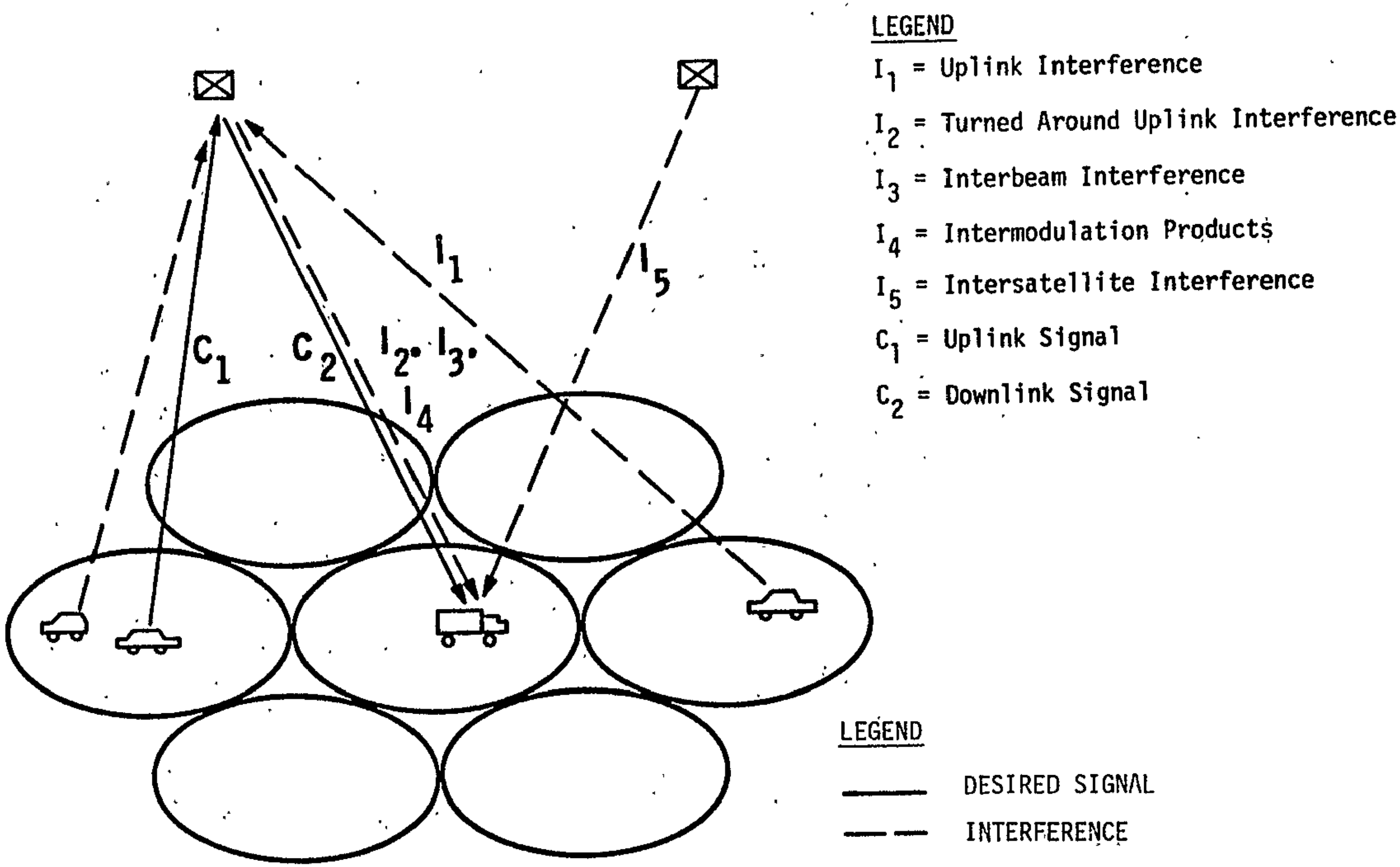


Figure E-1.
A Typical Interference Scenario
for a Mobile-to-Mobile Link

efficient modulation schemes. Thus, only cochannel interference will be considered. Since the mobile users are scattered all over the service area, the interference and the desired signal can be assumed to fade independently. If we let C_1 denote the received power of the desired signal, I_1 the received power of the interference, M the multipath fading, and I_B the interbeam isolation, then the cochannel interference-to-carrier ratio as received by the satellite is

$$I_1/C_1 = M/I_B \tag{E-1}$$

It should be pointed out that M and I_B are not expressed in decibels, and that $M \geq 1$ and $I_B \geq 1$. Implicit in Eq. (E-1) is that the uplink interference is received by the satellite through the sidelobes.

Upon receiving the uplink signal plus interference, the satellite amplifies and subsequently retransmits both the signal and interference to a terrestrial receiver. If the satellite has an on-board switching capability, the signals can be transmitted directly to the intended mobile user and, hence, complete the mobile-to-mobile link in a single hop. In the absence of on-board switching, the link can be completed using an additional hop which involves a backhaul link between the satellite and a gateway. In either case, the uplink interference is amplified and retransmitted to the mobile receiver, assuming that there is no intermediate signal processing either on-board of the satellite or in the gateway. The turnaround uplink interference travels the same path as the desired signal and, hence, fades simultaneously with the signal. Assuming the satellite transponder amplifies both the interference and the signal by the same factor, the

turnaround interference-to-signal ratio as received by the mobile receiver, denoted by I_2/C_2, is

$$I_2/C_2 = I_1/C_1 = M/I_B \tag{E-2}$$

where C_2 denotes the received signal power.

In addition to the turnaround uplink interference, the mobile receiver receives, through the sidelobes of the satellite antenna, downlink signals that are transmitted by the satellite and are intended for other users. These are termed as interbeam interference. Again, if one ignores the adjacent channel interference and denotes the received power level of the interbeam interference by I_3, then

$$I_3/C_2 = 1/I_B \tag{E-3}$$

Intermodulation products due to transponder nonlinearity are another source of interference. Unlike the interbeam interference and the uplink interference which can be controlled by reducing the antenna sidelobe level, intermodulation products can be reduced only by either operating the satellite amplifiers at a lower efficiency or by using linearized amplifiers. By letting I_4 denote the received intermod power, and I_M the carrier-to-intermod isolation, one obtains $I_4/C_2 = 1/I_M$.

The types of interference addressed thus far are all generated within a one-satellite system. For MSAT-2, which utilizes two satellites, an additional interference source exists. This is the intersatellite interference which includes all transmissions from the satellite with which the victimized receiver is not communicating. By letting I_5 denote the effective cochannel intersatellite interference as received by the mobile receiver and defining a parameter I_S, the intersatellite isolation, then

$$I_5/C_2 = 1/I_S \tag{E-4}$$

The intersatellite isolation is a function of many parameters, such as the satellite orbital separation, the directivity of the mobile antenna, antenna polarization, fading, and frequency plans for the two satellites. In a two-satellite system, the transmitted signals from these satellites travel different paths and, hence, they may be faded independently. Under the worst case, the desired signal may be fully faded while the interfering signal may suffer no fading at all. Multipath fading can thus cause serious degradation if it is not properly accounted for. For a fixed fading margin, the inter-satellite isolation can be increased by increasing the separation between the two satellites, by using a highly directive mobile antenna, dual polarization, and frequency diversity.

The total interference that the mobile terminal receives is the sum of I_2 through I_5, if we assume that all interference signals are independent and that their power can thus be summed. The signal-to-total-interference power ratio as received by the mobile user, denoted by $(C/I)_T$, is

$$(C/I)_T = C_2/(I_2 + I_3 + I_4 + I_5) \tag{E-5}$$

Substituting Eqs. (E-2), (E-3), and (E-4) for I_2, I_3, and I_5, and recalling that $I_4/C_2 = 1/I_M$, Eq. (E-4) becomes

$$(C/I)_T = (M/I_B + 1/I_B + 1/I_M + 1/I_S)^{-1} \tag{E-6}$$

or

$$(C/I)_T = [(M+1)/I_B + 1/I_{MS}]^{-1} \tag{E-7}$$

where

$$1/I_{MS} = 1/I_M + 1/I_S \tag{E-8}$$

The first term in the denominator of Eq. (E-6) is due to uplink interference, the second term is the downlink intrasatellite interbeam interference, the third term is the satellite intermodulation products, and the fourth term is the intersatellite interference. Eq. (E-7) has been plotted in Figure E-2(a) with I_{MS} as a parameter, and Eq. (E-8) in Figure E-2(b).

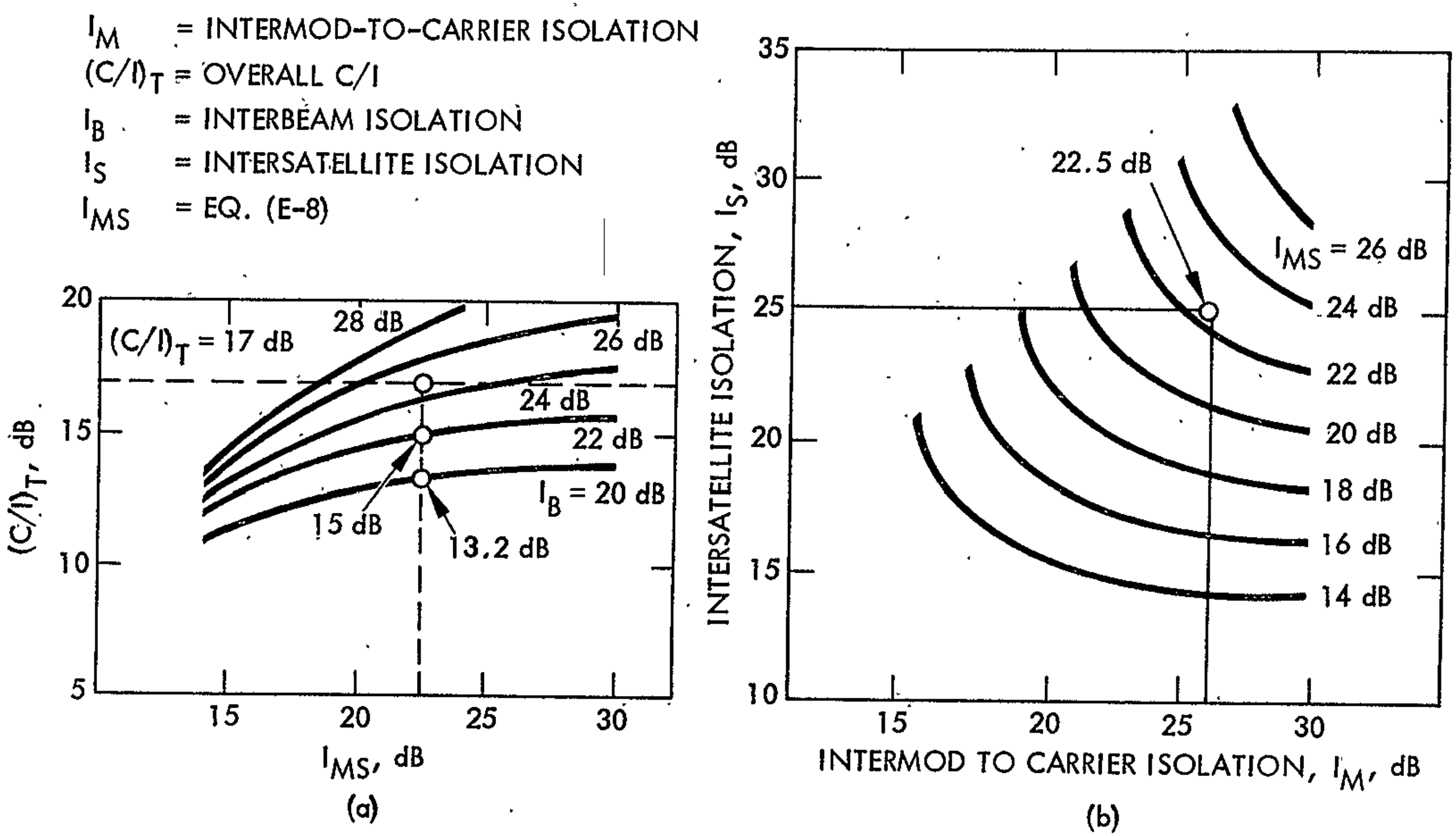


Figure E-2. Overall C/I, Intersatellite Isolation, Interbeam Isolation, and Intermod-to-Carrier Isolation (Mobile-to-Mobile).

Figure E-2 can be used to calculate the overall C/I if the intersatellite isolation, intermod isolation, and interbeam isolation are known. For example, if the intersatellite isolation is 25 dB and the intermod isolation is 26 dB, then the overall C/I is about 13.2 dB, 15 dB, and 17 dB for an interbeam isolation of 20 dB, 22 dB, and 25 dB, respectively.

E.2 MOBILE-TO-FIXED-STATION COMMUNICATION

The mobile-to-fixed-station case is different from the mobile-to-mobile case, in that its downlink is in the Ku-band (backhaul) and its uplink is the UHF band, while both uplink and downlink are UHF for the mobile-to-mobile case. Because the baseline scenario assumes a single backhaul beam with no frequency reuse, the intersatellite interference and downlink interbeam interference can be ignored. The only interference received by the fixed station is the turnaround uplink interference and the intermodulation products generated by the Ku-band power amplifier in the satellite.

Noting that the uplink interference situation is the same for the mobile-to-mobile and the mobile-to-fixed communications, the overall C/I is

$$(C/I)_T = (M/I_B + 1/I_M)^{-1} \qquad \text{(E-9)}$$

when M and I_B are as previously defined and I_M is the Ku-band carrier to the intermod protection. Eq. (E-9) is pictorially shown in Figure E-3.

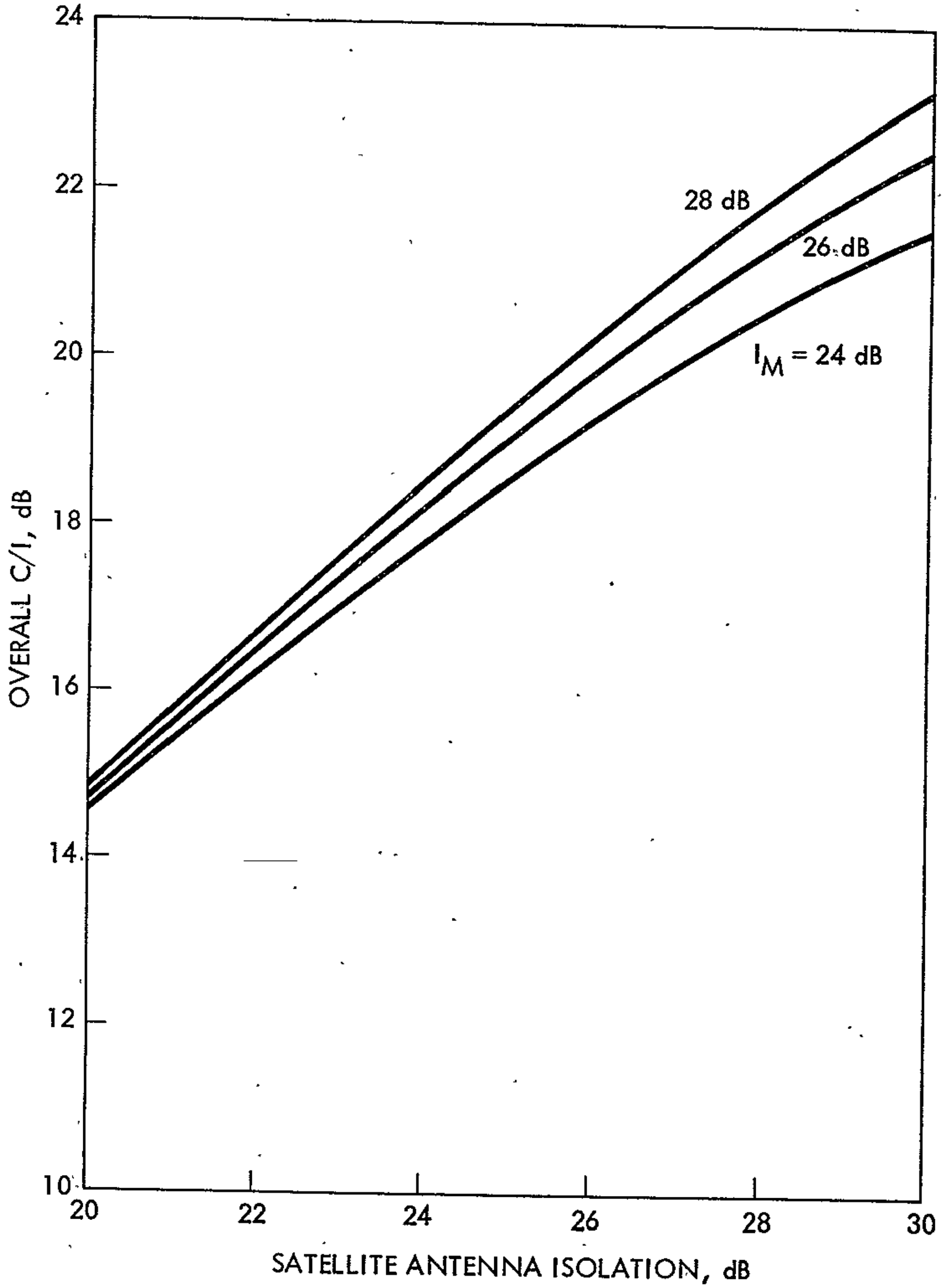


Figure E-3. Overall C/I vs. Satellite Antenna Isolation With I_M as a Parameter.
Mobile-to-Fixed Station.
I_M = Carrier-to-Intermod Ratio (Backhaul).

E.3 FIXED-STATION-TO-MOBILE COMMUNICATION

Similar to the mobile-to-fixed-station, the fixed-station-to-mobile communication involves a Ku and an UHF portion. The uplink is in the Ku-band and the downlink is in the UHF band. Assuming that the uplink interference is negligible, the overall C/I can thus be obtained from Eq. (E-1) by simply dropping the term due to uplink interference,

$$(C/I)_T = (1/I_B + 1/I_{MS})^{-1} \tag{E-10}$$

where I_B and I_{MS} are as previously defined. Eq. (E-10) is plotted in Figure E-4.

E.4 CONCLUSION

All major interference sources have been analyzed for their contribution toward the overall C/I. Methods to calculate the resulting overall C/I for a particular combination of intersatellite interference, interbeam isolation, and intermod levels have been presented in Figures E-2 to E-4. These curves conversely can be used to determine the required sidelobe level, intersatellite isolation, or intermod level in order to meet a prescribed C/I value. Results of this analysis will be used to facilitate the trade-off study described in Chapter 2.

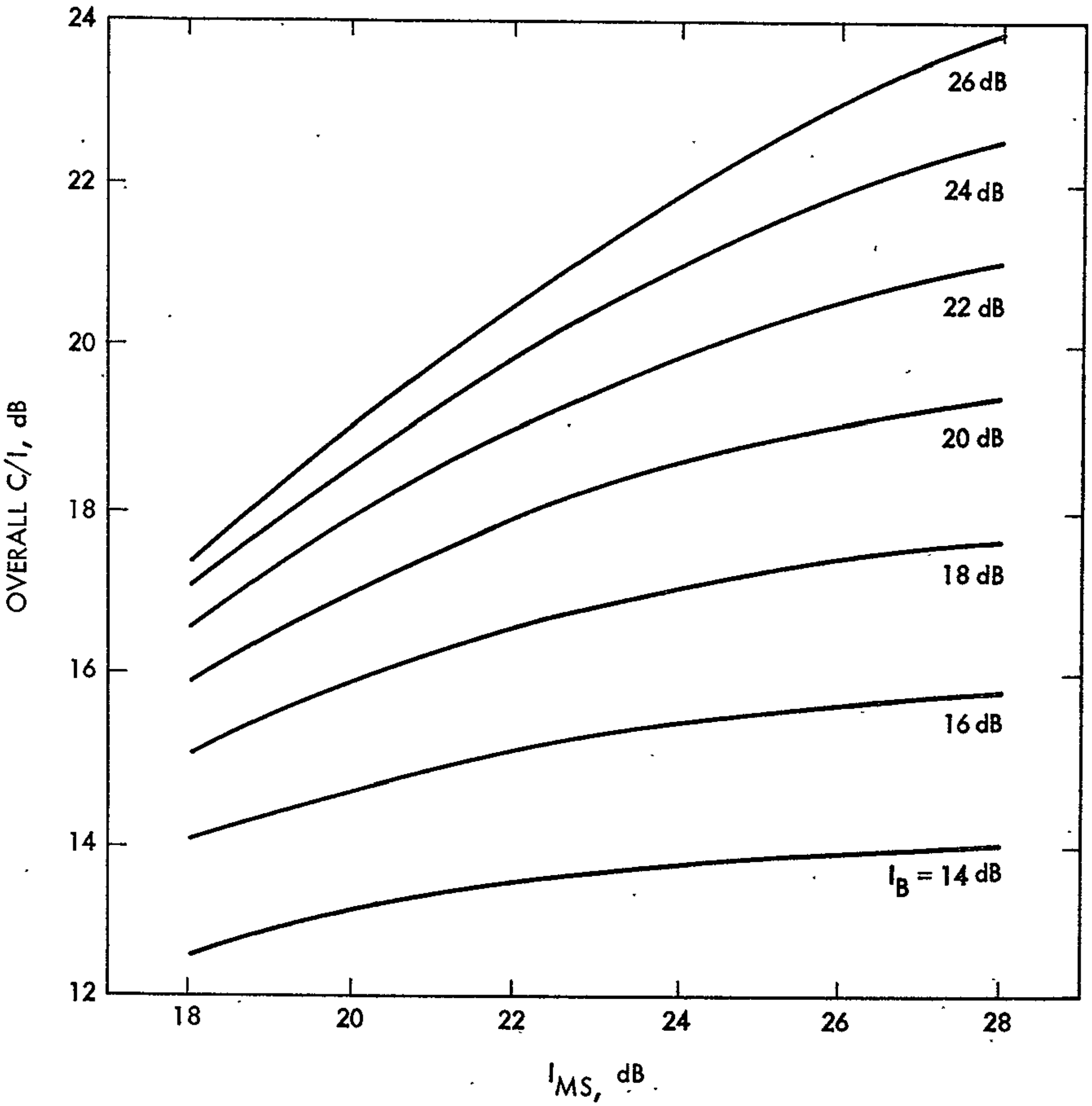


Figure E-4 . Overall C/I vs. I_{MS} for Selected Satellite Antenna Isolation.
Fixed Station-to-Mobile.
I_{MS} is Defined in Eq. (E-8).
I_B = Interbeam Isolation.

APPENDIX F

PROPAGATION IN THE MOBILE-SATELLITE COMMUNICATIONS ENVIRONMENT

F.0 INTRODUCTION

This appendix treats the various propagation effects which will be of interest to LMSS for the frequency range 0.5 to 50 GHz, but with specific attention to the UHF and L-band frequencies now under active consideration. The general approach is shown in Figure F-1. Here r_1 is the direct ray from the geostationary satellite to the receiver, and the effects of the ionosphere and troposphere on it are considered to be the same on the other two rays. These are: r_2, the specular or coherent ground reflected ray; and r_3, the so- called "diffuse component" which is made up of all the other signal components reaching the receiver (Beckmann and Spizzichino, 1963). It is frequently termed the "multipath component" although usage differs as to whether or not the multipath components include the specular reflection r_2. Our practice has been to consider the fading of the direct and ground specularly reflected components $(r_1 + r_2)$ to be an order of magnitude or so slower than that of the diffuse component; hence, it makes sense to first combine r_1 and r_2 and to consider the resultant as a steady signal for the purposes of combination with the diffuse component. This approach allows the use of Rician statistics (Rice, 1944) which deal with the combination of a steady component and a Rayleigh distributed component. The parameter involved, K, is the ratio of the specular to random power received.

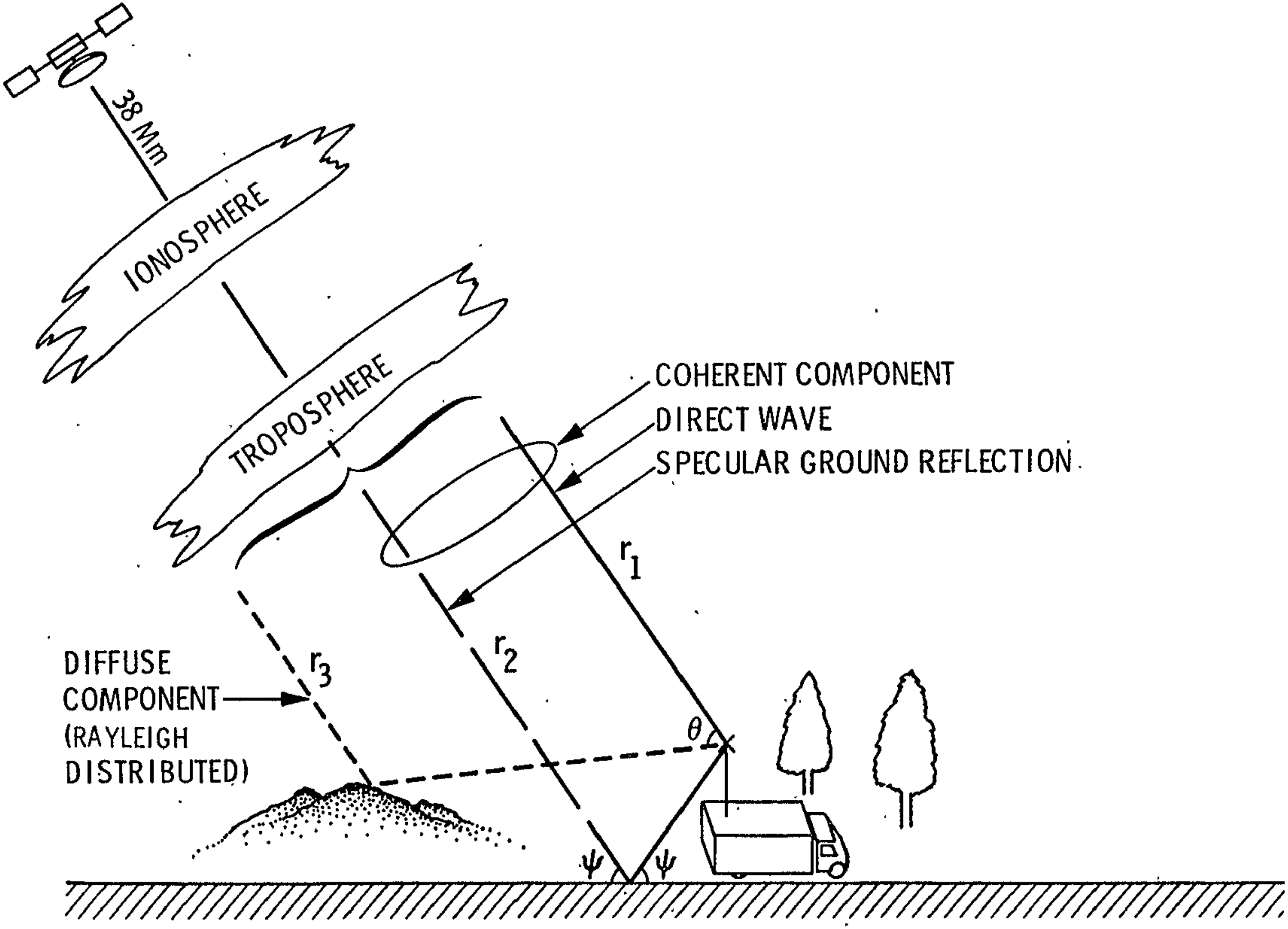
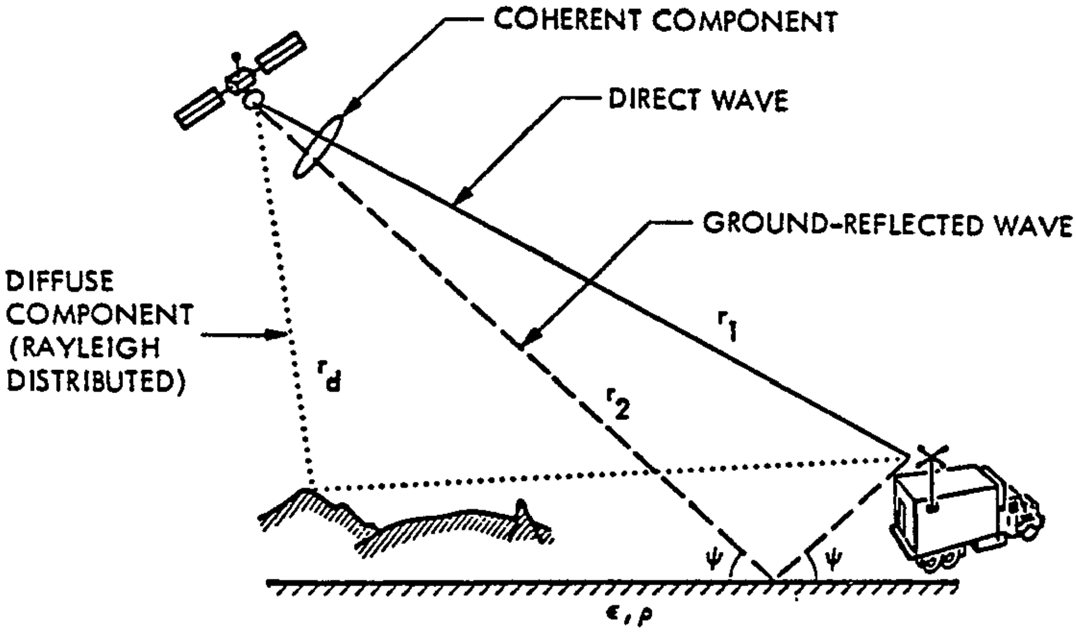


Figure F-1. Propagation Effects on Land Mobile Satellite Systems

This combination of $r_1 + r_2$, known as the "coherent component," is computed as shown in the relations below the pictorial diagram in Figure F-2. The free space level of the electric field E_o is determined from the transmitter power P_T, in watts, the transmitting antenna gain G_T above isotropic, and the distance d in meters. Attenuation of the direct wave in the ionosphere and the troposphere is accounted for by the "optical depth," τ, a term used in astronomy to represent a decrease in power. Hence, a value of $\tau = 1$ represents a decrease in signal power by exp(-1) or a decrease in field strength of exp(-1/2). This amounts to 4.34 dB and the unit of τ is the neper, inasmuch as it is defined the same way as the neper in transmission line terminology. Note however that the definition is in terms of power rather than voltage. As a consequence the optical depth neper is 4.34 dB rather than 8.68 dB for the transmission line neper.

F.1 IONOSPHERIC EFFECTS

The ionospheric effects we are concerned with above 500 MHz on earth-space paths are all related to free electrons. The term ionosphere is used loosely here to refer to all such ionization between the satellite station, assumed to be in a geostationary orbit, and the terrestrial mobile station. During the daytime, approximately 90% of the ionization is ionospheric (i.e., below about 600-km altitude) while only 10% is plasmaspheric (i.e., in the plasmasphere, above roughly 600 km). However at night this ratio may shift to 50/50. Shown in Figure F-3 is the Faraday rotation due to this ionization, as measured in Japan, which has been factored by use of the formulae in Figure F-4 to yield curves representing surface elevation angles of 20^{o} and 60^{o} at 850 MHz and 1600 MHz for high and low sunspot numbers.



$$\text{FREE SPACE } E_o = \left[(120\pi)\frac{P_T G_T}{4\pi d^2}\right]^{1/2} = \left[30\frac{P_T G_T}{d^2}\right]^{1/2} \tag{F-1}$$

$$\text{DIRECT WAVE } |E_{dir}| = E_o e^{-\frac{\tau}{2}} \tag{F-2}$$

AT MOBILE VEHICLE

$$\vec{E}_{total} = \underbrace{\vec{E}_{dir} + \vec{E}_{cgr}}_{E_{coh}} + \vec{E}_{dif} \tag{F-3}$$

$$|E_{coh}| = E_{dir}\left\{1 + \rho_s D R_o \exp i(\theta_R + \theta_d)\right\} \tag{F-4}$$

Figure F-2. The Ray Construction Used for Ground Multipath Modeling Along With the Mathematical Formulation. Symbols are Defined in (Smith, Cavanagh, and Flock, 1983).

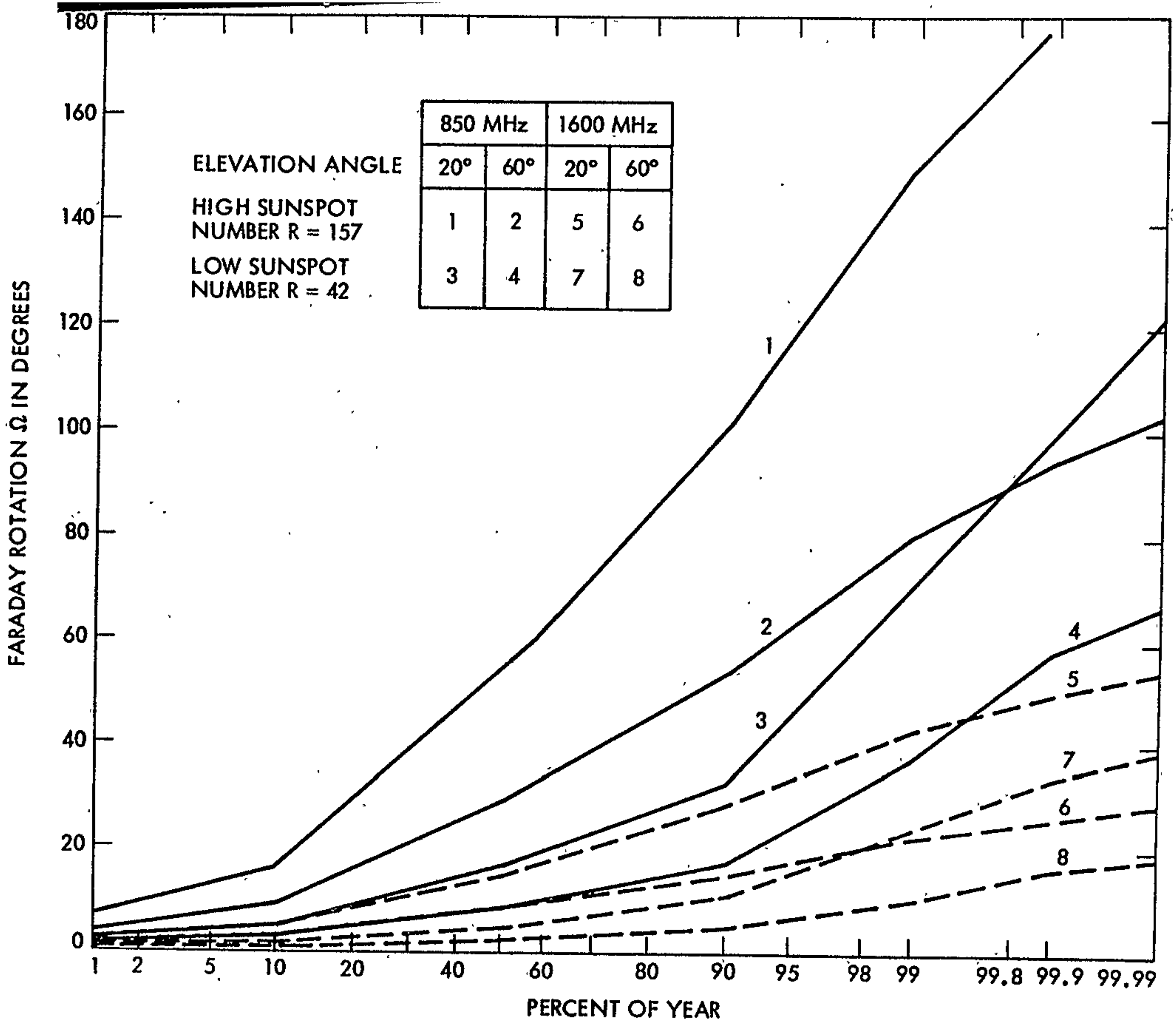


Figure F-3. Observed Faraday Rotation for Transmission From a Mid-Latitude Station to a Geostationary Satellite Derived from CCIR Report 263-5, Table VI (1977-78 and 1979-80 Measurements From Tokyo of Satellite ETS-II), After Vogel and Smith (1985)

$$\text{FARADAY ROTATION } \Omega(\text{deg}) = \frac{135}{f^2} \int_S B_L \, N \, ds \qquad \text{(F-5)}$$

$$\text{GROUP DELAY } \Delta t(\text{ns}) = \frac{133}{f^2} \int_S N \, ds \qquad \text{(F-6)}$$

$$\text{ABSORPTION } L_a(\text{dB}) = 1.15 \times 10^{-3} \int_S \frac{N\nu}{f^2} \, ds \qquad \text{(F-7)}$$

$$\text{DISPERSION } \frac{dt}{df} (\text{s/Hz}) = \frac{2.69 \times 10^{-7}}{f^3} \int_S N \, ds \qquad \text{(F-8)}$$

N = ELECTRONS PER m^3

f = FREQUENCY IN HERTZ

B_L = COMPONENT OF EARTH MAGNETIC FIELD IN DIRECTION OF PROPAGATION

ν = COLLISION FREQUENCY (ELECTRONS)

Figure F-4. Equations Employed to Calculate the Ionospheric Effects on Transionospheric Signals in the Frequency Range 0.5 to 50 GHz (in S.I. Units)

Shown in Table F-1 are values of the various ionospheric effects for three frequencies of interest: 850 and 1600 MHz and 20 GHz for an elevation angle of 30^{o}. These may be roughly related to the 20^{o} elevation angle curves of Figure F-3 by assuming that the total electron column (TEC) at a 20^{o} elevation angle compared to that at 30^{o} is in the ratio of 5:4. For example, if Faraday rotation is taken to be linearly related to TEC, then the value of 150^{o} at 850 MHz in Table F-1 relates to 187^{o} at a 20^{o} elevation angle in Figure F-4. This is seen to occur less than 0.1% of the time for high sunspot numbers (curve 1) and to be negligible at low sunspot numbers.

The predicted Zurich annual mean sunspot number for March 1985 is 30 (Telecommunication Journal, January 1985); and the expectation, based on the mean behavior, is that the next minimum will occur in 1987 to 1989 and the next solar maximum in the neighborhood of 1991 to 1993.

F.2 TROPOSPHERIC EFFECTS

For the elevation angles above about 5^{o} (which are assumed for this appendix), tropospheric refractive effects will be negligible for communication applications. Attentuation due to the atmosphere and weather effects [see Eq. (F-10) in Fig. F-5] will be negligible at 850 and 1600 MHz but not at 20 GHz. These are summarized in Table F-2 and the relations used to determine them are given symbolically in aggregate in Fig. F-5 [Eq. (F-10)], for the clear atmosphere in Eq. (F-11), for the added attenuation due to liquid

Table F-1.

Estimated maximum ionospheric effects for elevation angles of about 30^{o} one-way traversal assuming a zenith electron column of 10^{18} electrons/m^2

	Frequency Dependence	Magnitude 850 MHz	1600 MHz	20 GHz
Faraday Rotation	$1/f^2$	150^{o}	42^{o}	$>0.3^{o}$
Propagation delay	$1/f^2$	0.35 s	0.1 s	> 1ns
Variation in direction of arrival	$1/f^2$	16 sec of arc	4.7 sec of arc	0.03 sec of arc
Refraction	$1/f^2$	> 50"	> 14"	> 0.09 sec
Absorption (mid-lats)	$1/f^2$	>0.014 dB	>0.004 dB	$>2.5 \times 10^{-5}$dB
Dispersion	$1/f^3$	0.65 nsec/MHz	0.1 nsec/MHz	0.05 psec/MHz
Scintillation	Variable	(a)	(a)	–

(a) May be a factor at the 1% time level at equatorial latitudes and for transauroral zone path.

Table F-2

Estimated tropospheric effects for an elevation angle of 30°, one-way traversal

Effect	Magnitudes (dB) for selected operating frequencies						
	0.85 GHz	1.6 GHz	20 GHz	45 GHz	70 GHz	94 GHz	140 GHz
<u>clear air absorption</u>[a] (dB)							
$3g/m^3$	0.06	0.07	0.28	0.96	4.41	1.45	2.29
$7.5g/m^3$	0.06	0.07	0.59	1.25	5.07	2.65	5.16
$17g/m^3$	0.06	0.07	1.18	1.88	6.46	5.18	11.22
<u>cloud attenuation</u>[b] (dB)							
$0.5\ g/m^3$, 1 to 2 Km hgt.	<.01	<.01	0.4	1.7	3.4	5	7.5
	<.01	<.01	1.6	6.8	13.6	20	30.0
<u>rain attenuation</u>[c] (dB)							
5 mm/hr	<.01	<.01	3.26	12.23	19.70	25.13	27.85
25 mm/hr	<.1	<.1	19.01	55.0	78.12	81.51	86.95
<u>Refractive Multipath</u>	$\pm.5$	$\pm.5$	±1	±1	±1.5	±1.5	± 2

a. Derived from Report 719 Annex 11 using t = 15° C. Values for other elevation angles above $\theta = 10°$ may be obtained by multiplying the magnitudes (dB) by $(\csc\theta)/2$.

b. Derived from specific attenuation values given in Report 721 using models from Slobin 1982. For other elevation angles the attenuation may be estimated for $\theta \geq 10°$ by multiplying the dB magnitudes by $(\csc\theta)/2$.

c. Derived from Report 564 section 6.1.2 and Report 721. The significance of the two rain rates 5mm/hr and 25 mm/hr may be assessed from Report 563, Fig. 11 and Table 1.

$$\left| E_{dir} \right| = E_o \, e^{-\frac{1}{2}\tau} = E_o \exp\left\{ -\frac{1}{2} \frac{A(dB)}{4.34} \right\} \qquad \text{(F-9)}$$

$$\text{ATTENUATION } A(dB) = A_{ion} + A_{gas} + A_{cloud} + A_{rain} \qquad \text{(F-10)}$$

$$A_{gas} = \int_S \left(\gamma_{O_2} + \gamma_{wv} \right) ds \qquad \text{(F-11)}$$

$$A_{cloud} = \int_S \gamma_{lw} \left(r_o, \, \rho, \, T \right) ds \qquad \text{(F-12)}$$

$$A_{rain} = \int_S \left\{ \gamma_{lw} \left(r_1, \, \rho, \, T \right) + \gamma_{scat} \left(r_1, \, \rho, \, T \right) \right\} ds \qquad \text{(F-13)}$$

Figure F-5. Mathematical Formulation of Tropospheric Attenuation

water in clouds in Eq. (F-12) and the added attentuation due to rain in Eq. (F-13). The symbol γ is used for specific attentuation, and the subscripts refer to molecular oxygen, water vapor, and liquid water content (as a function of location, density, and temperature). In all cases s refers to the ray path.

F.3 MULTIPATH EFFECTS

The multipath effects of interest here are those due to reflections from surface objects: surface roughness, hills, trees, buildings, water waves, etc. Atmospheric multipath is not a significant factor. Figure F-2 provides a pictorial representation of the processes of concern. The composition of the resultant field strength is given in Eq. (F-3) in Fig. F-2 which expresses the vectorial addition first of a direct and coherent ground reflected wave to form a coherent component, and then the combination of the coherent component with a diffuse component to form the total wave. The direct wave is defined by Eqs. (F-1), (F-2), and (F-9) in Figs. F-2 and F-5. The coherent component is given by Eq. (F-4), Fig. F-2, where the symbols are defined in Figure F-6 under Eq. (F-14).

The plane earth reflection Eqs. (F-4) and (F-14) is a function of earth conductivity, dielectric constant, and frequency. Typical values of these ground constants are given in Figure F-7. A computation of the reflection coefficients for vertical and horizontal polarization for 15 GHz is shown in Figure F-8. The computations are actually based on the DC (low frequency) values as shown in Figure F-7, but they are not bad except for sea water. Figure F-8 serves to illustrate an interesting phenomenon in the

$$R_{coh} = \rho_s D R_0 \qquad \text{(F-14)}$$

R_0 SMOOTH EARTH REFLECTION COEFFICIENT

D DIVERGENCE FACTOR FOR CURVED EARTH

ρ_s TERRAIN ROUGHNESS FACTOR

$$\text{WHERE} \quad \rho_s = e^{-\frac{(\Delta\phi)^2}{2}} \qquad \text{(F-15)}$$

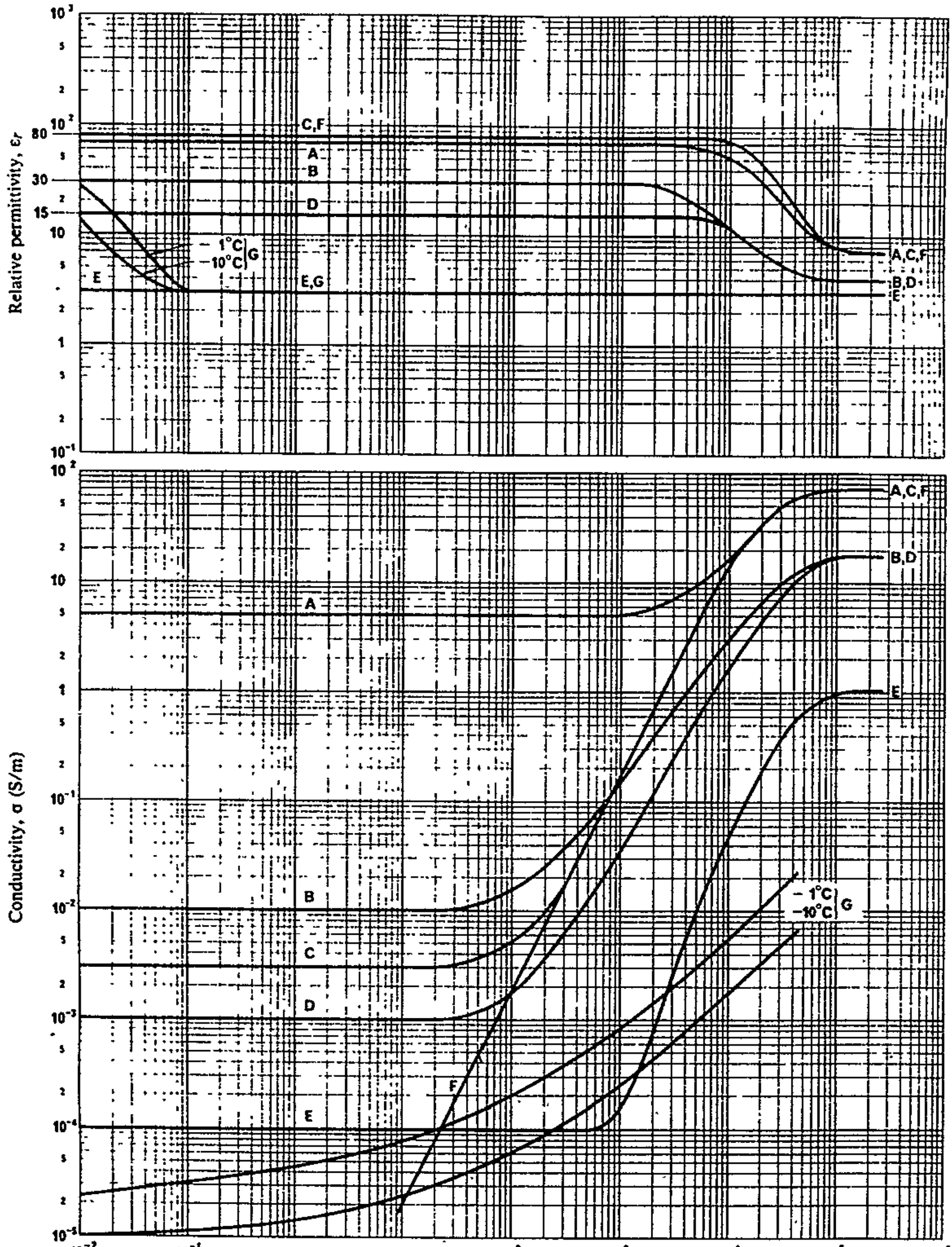
$$\text{AND} \quad \Delta\phi = 4\pi \left(\frac{\Delta h}{\lambda}\right) \sin\psi \qquad \text{(F-16)}$$

Δh STANDARD DEVIATION OF DISTRIBUTION OF HEIGHTS OF IRREGULARITIES

ψ GRAZING ANGLE

λ WAVELENGTH

Figure F-6. Formulation of the Reflection Coefficient for Specular Reflection Including the Terrain Roughness Factor (After Beckmann and Spizzichino, 1963)



A: sea water (average salinity), 20° C
B: wet ground
C: fresh water, 20° C
D: medium dry ground
E: very dry ground
F. pure water, 20° C
G: ice (fresh water)

Figure F-7. Permittivity and Conductivity of Various Surfaces as a Function of Frequency (CCIR Recommendation 527-1, 1982)

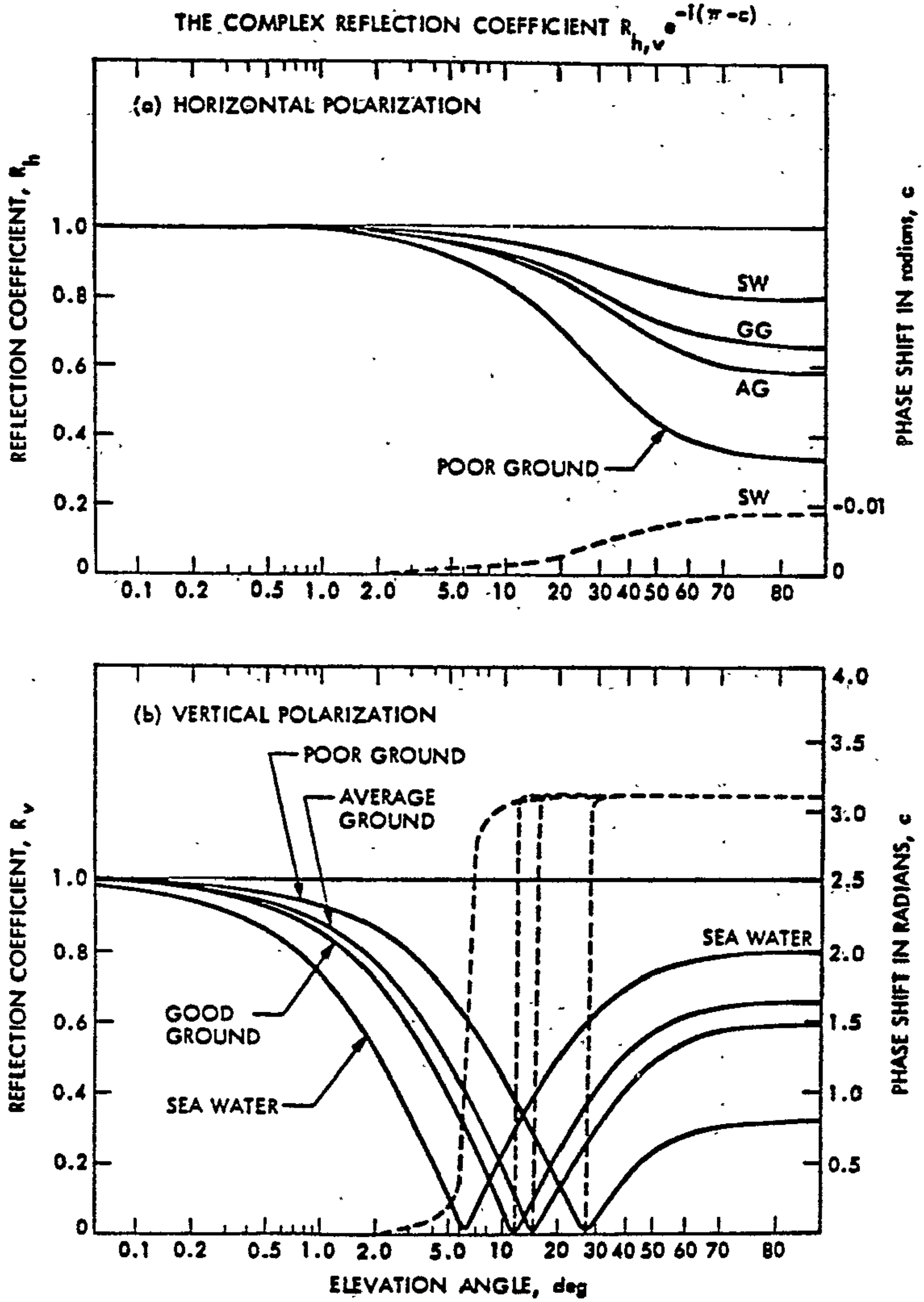


Figure F-8. Complex Plane-Earth Reflection Coefficient for 15 GHz, Using Static Ground Constants (Smith, Cavanagh, and Flock, 1983)

variation of the coefficient for vertical polarization with an elevation angle, namely the 180° (or near 180°) phase shift which occurs right around the Brewster angle (where the reflection coefficient drops to zero). The effect of this on a circularly polarized transmission is that the reflected wave will switch at the Brewster angle from, say, right-hand to left-hand elliptically polarized, if the direct wave were right-hand circularly polarized. Shown in Figure F-9 is a modern computation for the vertical polarization case (courtesy of John Cavanagh) for 1 GHz which does include the proper complex values of the ground coefficients. Sea water is seen to be quite different from Figure F-7 but the ground cases (good, average, poor) are little changed. This is a consequence of their being in the dielectric regime where frequency is no longer a factor.

The divergence factor D in Eqs. (F-4) and (F-14) is a purely geometrical term which may be taken as unity for the land mobile case but becomes a factor in aeronautical mobile considerations. It is given in Figure F-10 for the sake of completeness. The curve parameter refers to the altitude of the antenna above the reflecting surface.

The terrain scattering factor given in Eqs. (F-15) and (F-16) is the classical formulation found in Beckmann and Spizzichino (1963). A problem with this formulation is the excessively high loss values obtained for large values of the argument, $\Delta\phi$ (shown on the abscissa of Figure F-11). A more recent formulation (Miller, Brown, and Vegh, 1984) adds an additional factor, the modified Bessel function of the same argument, which gives more reasonable values of the loss due to the terrain roughness factor.

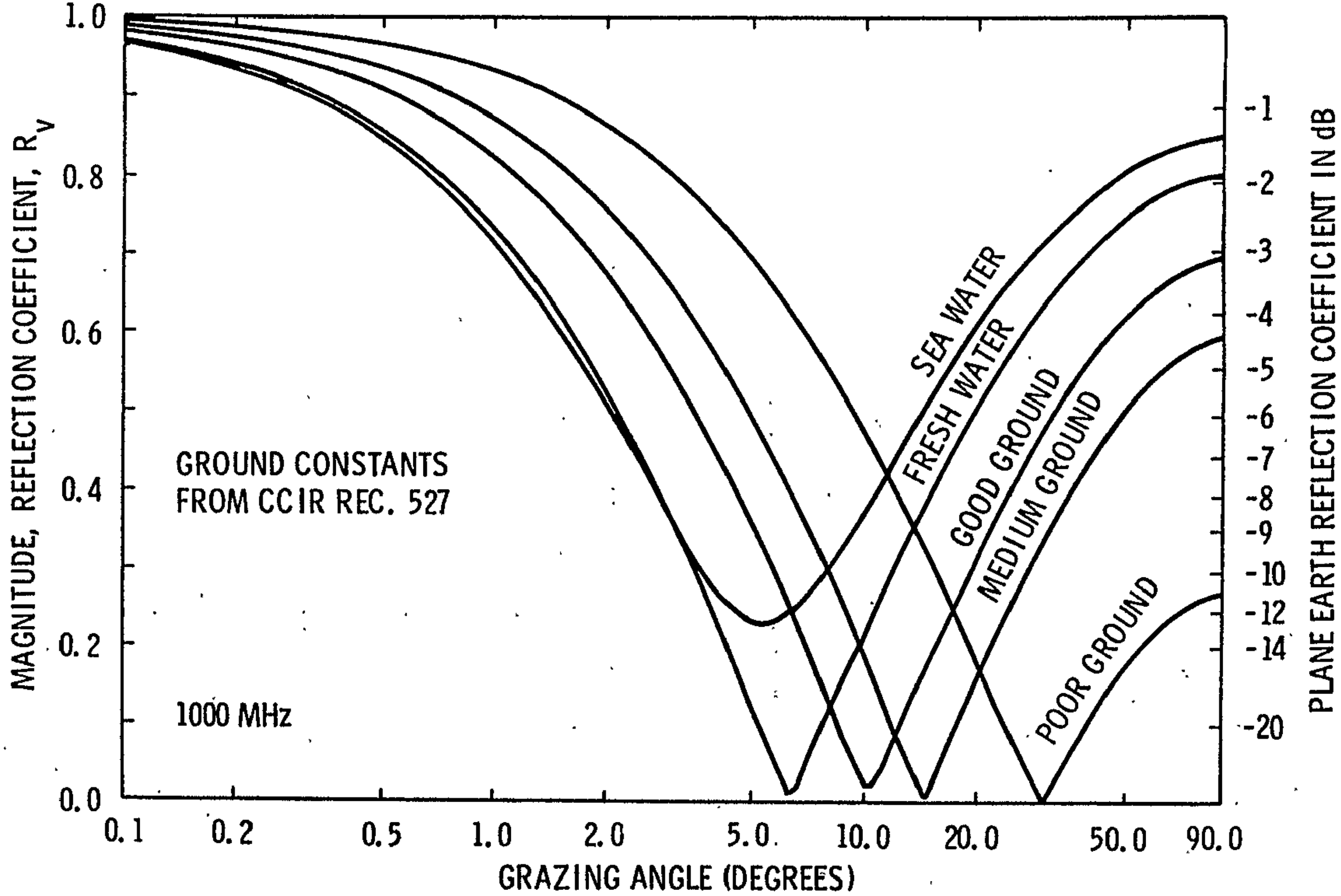


Figure F-9. Plane-Earth Reflection Coefficients for 1000 MHz for Vertical Polarization (Courtesy of John Cavanagh, NSWC)

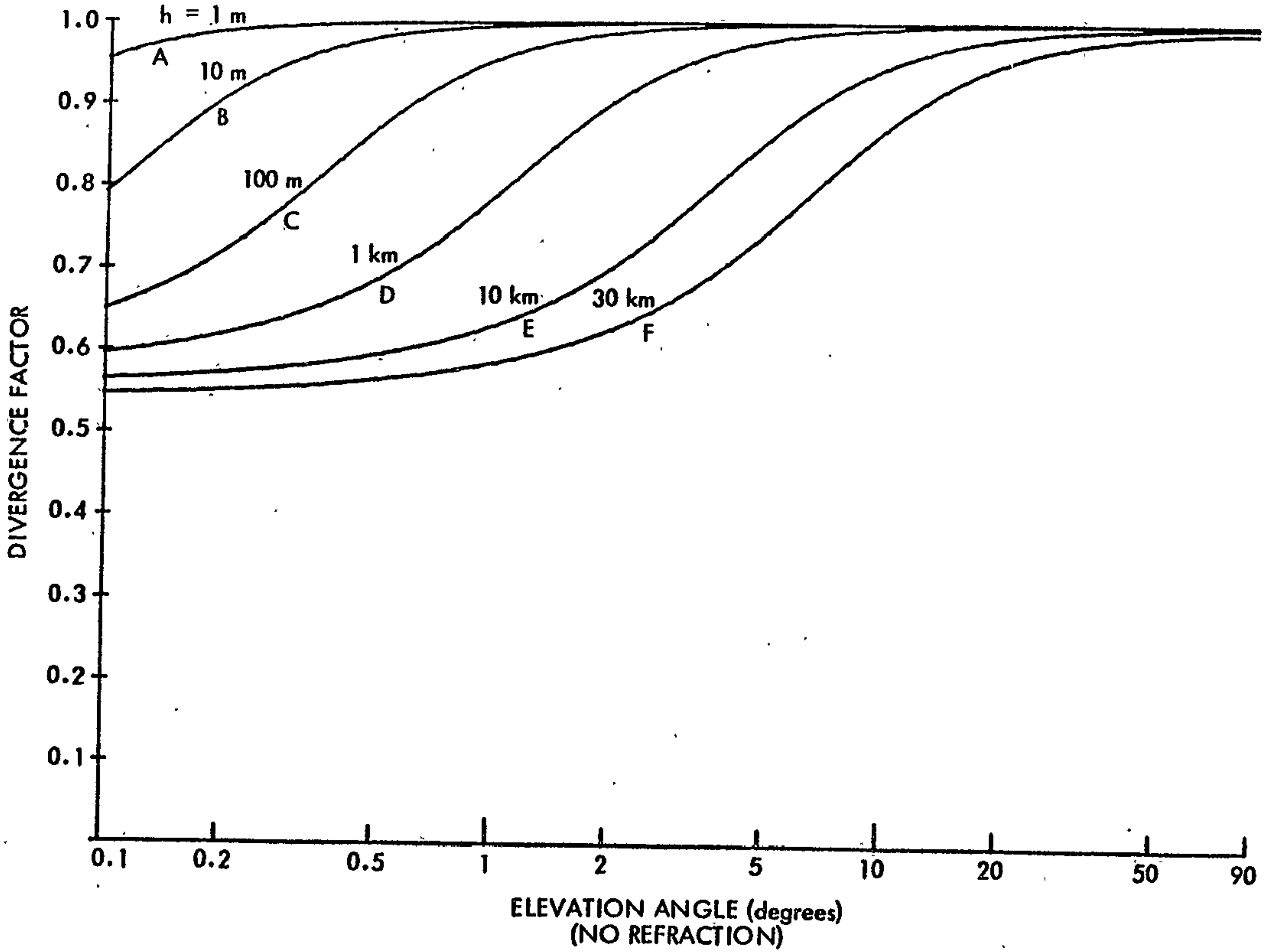


Figure F-10. Smooth-Earth Divergence Factor for Transmission From a Satellite to a Mobile Station With an Antenna at the Indicated Altitude (Courtesy of John Cavanagh)

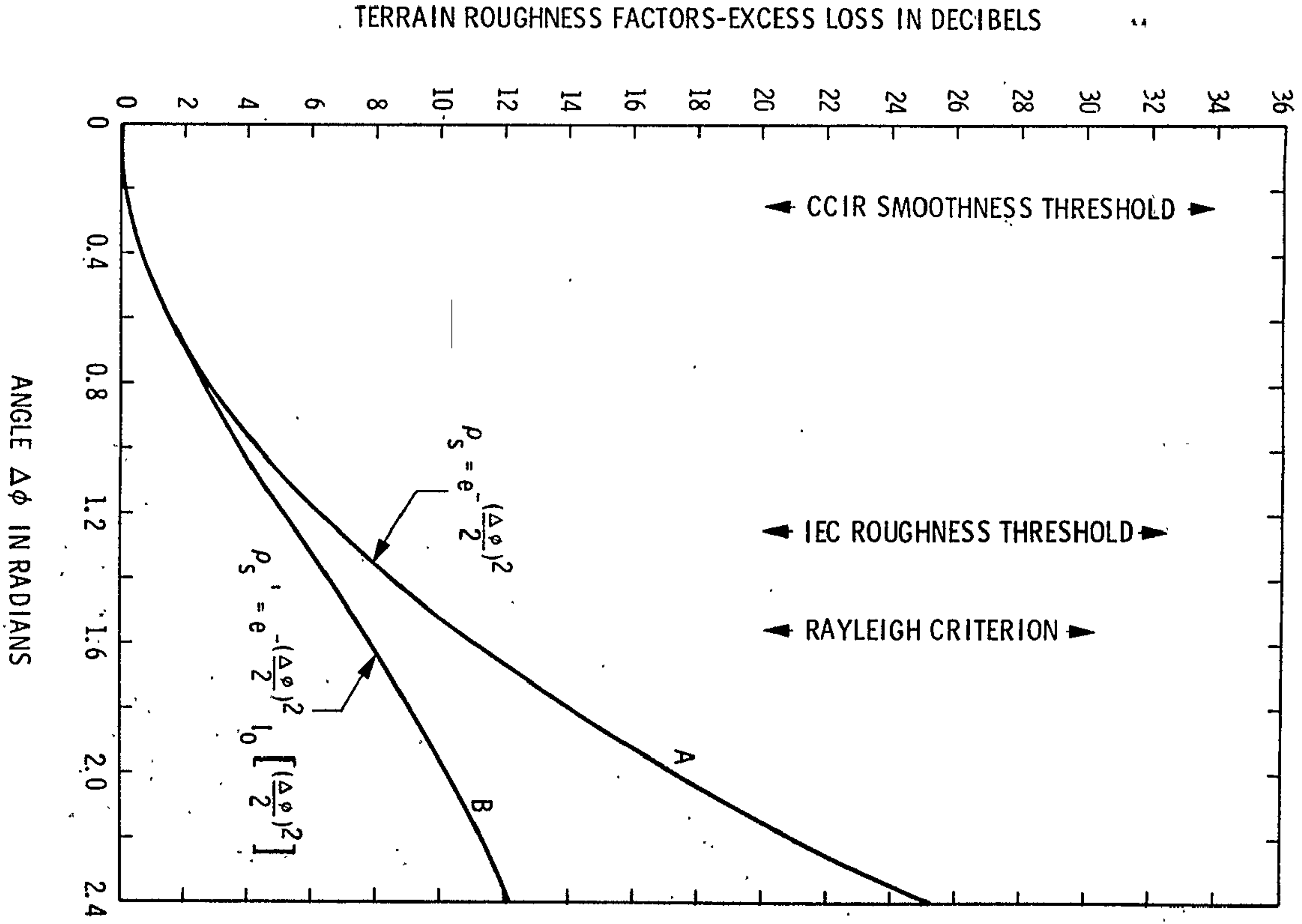


Figure F-11. Terrain Roughness Factor as a Function of the Phase Angle $\Delta\phi$ (Beckmann and Spizzichino, 1963, Upper Curve). Miller, Brown and Vegh, 1984, Lower Curve; After Vogel and Smith (1985)

The reflection coefficient for circular polarization has been treated by Jamnejad (1985) and Flock (1985) and the latter treatment also considers terrain effects in a modern manner. A point which is not immediately apparent in Figure F-11 is that $\Delta\phi$ increases with elevation angle and with frequency. Hence, terrain of a given roughness will cause more loss to the specularly reflected wave (from the vicinity of the first Fresnel zone) the higher the elevation angle, and the higher the frequency. This follows from Eq. (F-15).

It is generally desirable to suppress the specular ground-reflected component as much as possible in the mobile case. This is because it is just as likely to combine out-of-phase with the direct component as in-phase. The terrain roughness factor helps to depress it, but it is advantageous as well if the antenna pattern is such as to depress the specular term by 5 to 10 dB relative to the direct wave.

The final term in Eq. (F-3), the so-called diffuse component, is beyond the scope of this appendix, and is in fact, poorly understood. Experimental values are generally in the vicinity of 8 to 14 dB below the direct wave with a distribution of angles centered on the horizontal. The classical reference for the diffuse component is Beckmann and Spizzichino (1963). More recent work, such as that of Bahar (1984) for the bi-static radar case, can possibly be utilized.

F.4 FOLIAGE ATTENUATION

The effect of trees on LMSS has been found to be a more serious problem during the balloon experiments carried out for NASA by the University of Texas than had been anticipated. It is clearly an area of significant concern.

The foliage attentuation problem has been studied in the past largely for the ground-to-ground communications case (Schneider, 1984) the results of which are only marginally relevant to the LMSS problem. The work which has been done for LMSS, which includes foliage effects, is reviewed in papers by Flock, Butterworth, Vogel, and Stutzman in the Proceedings of the JPL Propagation Workshop (Smith, Ed., 1985). The current results indicate that the probability distribution is a mixture between Rician (as one would expect from terrain multipath) and log-normal (as one would anticipate for foliage attenuation). The analysis further indicates that the combination of the coherent and diffuse components from Eq. (F-3) should be such that

$$\vec{E}(\text{total}) = B\,\vec{E}(\text{coherent}) + C\,\vec{E}(\text{diffuse}) \qquad \text{(F-17)}$$

where B and C represent foliage attenuation and may be different for the two components. While rays r_1 and r_2, representing the specular and direct components, respectively, will also suffer somewhat different foliage attentuation, they are in the same vertical plane with the satellite and the mobile antenna, so that using the same foliage attentuation is more reasonable than with the coherent and diffuse case.

The present expression recommended by the CCIR (Report 236-5 MOD I) for foliage attentuation L for the case where the antenna is near a small grove of trees is

$$L = 0.2\ f^{0.3} d^{0.6} \quad \text{db} \qquad \text{(F-18)}$$

where f is frequency in gigaherz and d is distance in meters. An alternate expression which also fits the data in the 500 to 2000 MHz region pretty well is

$$L = 0.3\ f^{0.8} d \quad \text{db} \qquad \text{(F-19)}$$

This expression is a fair fit to the CRC data (Butterworth, 1985) and to that of Saxton and Lane (1955). It has the further advantage that it does not appear to violate Lambert's law in that the loss in dB would be expected to vary linearly with the distance, d. Needless to say, this question deserves further study.

Shown in Figure F-12 are plots of cumulative distribution of received signal levels for the CRC and Texas (Vogel and Torrence, 1983) balloon experiments for NASA for different ranges of elevation angles. The Vogel and Torrence data is for East Texas and Louisiana, a region of more than average foliage attentuation.

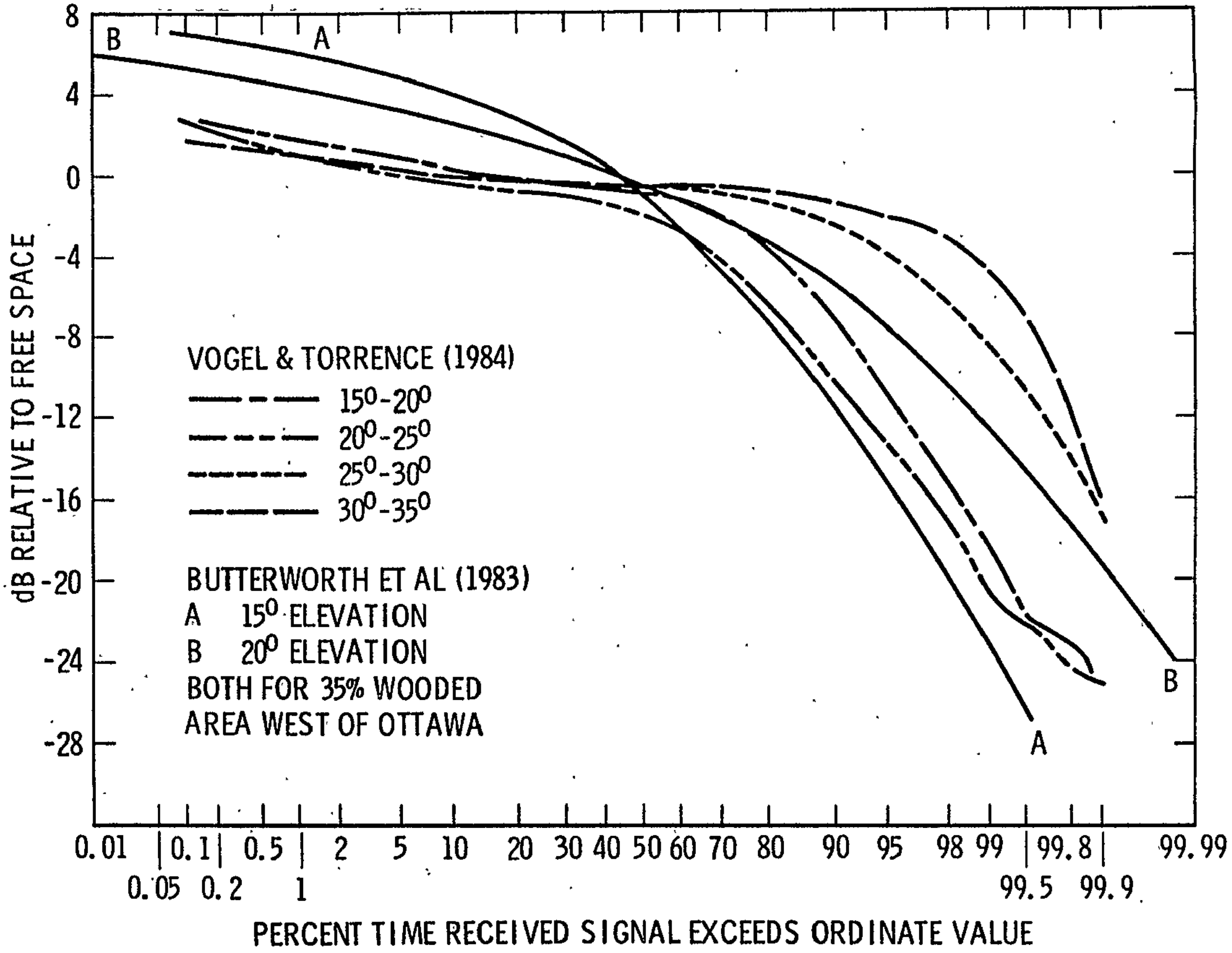


Figure F-12. Comparison of Data From Vogel and Torrence (1984) With Helicopter Data Obtained by Butterworth, et al (1983). Inconsistency Between the 15° to 20° Curve and 20° to 25° Curve is Due to Excess Foliage Attenuation in the Latter Data Sample

REFERENCES

Beckmann, P. and A. Spizzichino [1963] The Scattering of Electromagnetic Waves from Rough Surfaces, A Pergamon Press Book, The MacMillan Company, New York.

CCIR [1982] Recommendations and Reports of the International Consulative Committee (CCIR), 1982; XVth Plenary Assembly, Geneva, 1982; XVth Planery Assembly, Geneva, 1982; International Telecommunication Union, Geneva.

- Recommendation 527-1, Electrical characteristics of the surface of the Earth; Volume V, pp 57-59.

- Report 263-5, Ionospheric effects upon Earth-space propagation; Volume VI, pp 124-149.

Flock, W. L. [1985] Draft Revision of chapter 6: Terrain effects and multipath propagation, NASA Reference Publication 1108 (released December, 1983); draft revision distributed at the MSAT-X Propagation Workshop JPL, Jan. 30/31, 1985.

Jamnejad, V. [1985] Ground multipath in Topex's precision orbit determination tracking system, JPL IOM 3365-84-003; January 9, 1985.

Miller, A. R., R. M. Brown, and E. Vegh [1984] New derivation for the rough-surface reflection coefficient for the distribution of sea wave elevations, IEE Proceedings, Vol. 131, Pt. H, No. 2, April, 1984.

Rice, S. O. [1944] Mathematical analysis of random noise. Bell Syst. Tech. J., No. 3, 1944 and No. 1, 1945.

Smith, E. K., Editor [1985] Proceedings of the MSAT-X Propagation Workshop, JPL January 30-31, 1985; JPL D-2208 (internal document), March 1985.

Smith, E. K., J. F. Cavanagh, and W. L. Flock [1983] Propagation effects for land mobile satellite systems. URSI-IEEE National Radio Science Meeting, Boulder, CO, 5-7 January 1983.

Vogel, W. J., and E. K. Smith [1985] Propagation considerations in land mobile satellite transmission. MSAT-X Report No. 105, 24 January 1985.

Appendix G

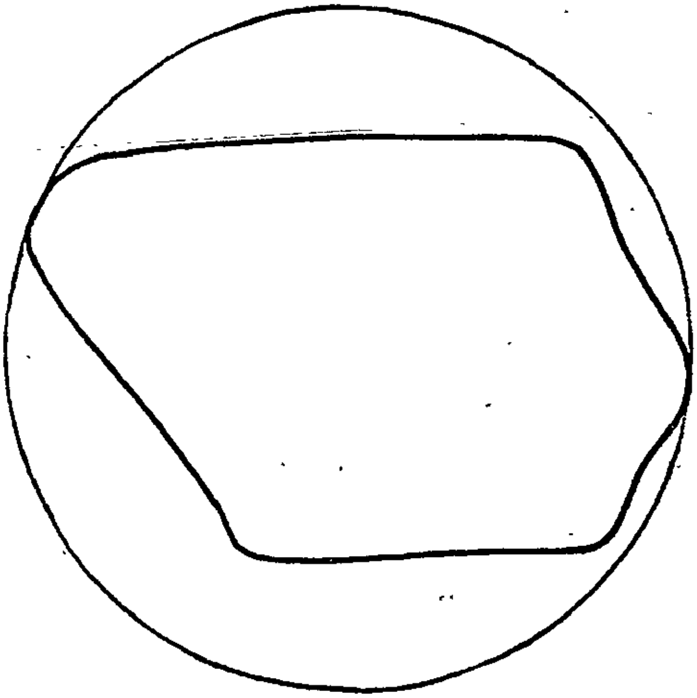
CHANNEL CAPACITY AND POWER REQUIREMENT TRADE-OFFS IN MULTIBEAM ANTENNA SYSTEMS

Multibeam antennas are usually proposed in satellite communications systems in order to increase the channel capacity by frequency (or time) reuse in different beams. Although the effect of reuse on the number of available channels is fairly straightforward, its effect on the total power requirement is sometimes not well understood. Here we present a brief definition of various terms and parameters involved, and then give some simple, useful formulas relating these parameters.

W		Total frequency bandwidth	(repeat time interval)
w		Channel bandwidth	(channel time slot)
M	$=$	W/w	Number of distinct channels in the total band
N		Number of beams	
n		Number of beams with distinct frequency (time) bands (number of sub-bands)	
r	$= 1/n$	Frequency (time) reuse factor	
N_r	$= rN$	Number of times each frequency band (time slot) is reused (number of beams with the same frequency (time) assignment)	
M_N	$= N_r M = rNM$	Total number of channels (system capacity) in an N beam reuse system	
g		Single beam antenna gain	
g_N		Multiple beam (N) antenna gain	
P		Total transmitted power in one beam system	
P_N		Total transmitted power in the N beam system	
U_c		Effective isotropically radiated power (EIRP) per channel	

The following two cases will be considered and compared. (See Fig. G-1.)

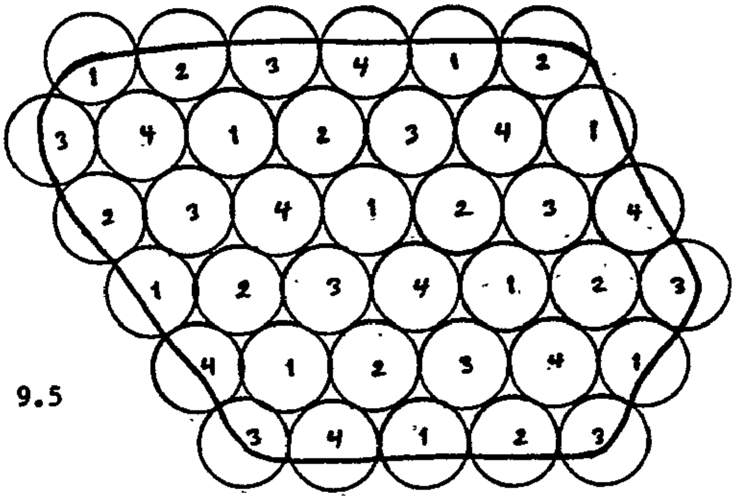
I. Single beam coverage – with one beam covering the entire area of interest on the ground, antenna gain of g, and total number of distinct channels M, the EIRP per channel is



(a) Single beam coverage, antenna gain, g
M channels, total power P

Band (1): 10 beams
Band (2): 9 beams
Band (3): 10 beams
Band (4): 9 beams

Average reuse number $N_r = 9.5$



(b) Multiple beam coverage, $N=38$, gain $g_N \geq Ng$
Reuse factor $r = 1/4$, $R = rN = 9.5$,
$M_N = 9.5M$, $P_N \leq P/4$.

Figure G-1. Comparison of Single and Multiple Beam Systems -- An Example

$$U_c = g(P/M) \qquad \text{(G-1)}$$

in which P is the total transmitted power. There is, of course, no reuse (frequency or time) possible in this case, except through polarization diversity which is not the subject of this memo.

II. Multiple beam coverage - if the same designated area is now covered by N beams, the gain of each beam is increased by approximately a factor of N

$$g_N \geq Ng \qquad \text{(G-2)}$$

This is because the gain increases linearly with the decrease in the beam coverage area. The inequality sign is due to the fact that in the single beam case, due to the irregularities of the boundary, the beam size is actually larger than the coverage area [Fig. G-1(a)] and a part of the power is wasted outside the desired region. As the number of beams increases, it is possible to follow more closely the boundary of the coverage area [Fig. G-1(b)].

With N beams one has the flexibility of increasing the channel capacity, decreasing the total power requirements of the system or a combination of the two. Thus, due to the spatial diversity of the beams (different beams covering different areas) a given frequency band (time interval) can be reused in different beams. This may be accomplished in many ways. A simple technique would be to divide the entire allocated frequency band (repeat time interval) into N equal subbands, and assign each subband to every nth beam, in a regular pattern [Fig. G-1(b)]. Let's define a frequency (time) reuse factor

$$r = 1/n \quad ; \quad (1/N) \leq r \leq 1 \qquad \text{(G-3)}$$

In an N-beam system each frequency band (time interval) is, on the average, repeated (reused) in $N_r = rN$ beams. In a full reuse system (r=1) each band

is reused N times. When r is minimal ($r=1/N$) there is no frequency reuse and each band is used exactly one time. Usually due to interference from adjacent beams a full frequency reuse system is practically impossible (it would require sector beams, that is, beams that are uniform within a given region and zero outside), but depending on application and acceptable levels of interference, the reuse factor selected can be as high as 1/4.

The overall system capacity (total number of channels with reuse) in an N beam system with frequency reuse factor, r, is

$$M_N = rN\,M \tag{G-4}$$

The EIRP per channel can be obtained as

$$U_c = g_N \frac{P_N}{M_N} = Ng \frac{P_N}{M_N} = g \frac{P_N}{rM} \tag{G-5}$$

in which Eq. (G-2) with an equality sign has been utilized, and P_N is the total power in N beams. Since the EIRP per channel must be equal in the single and multiple beam cases, from Eqs. (G-1) and (G-5) it follows that

$$P_N = rP \tag{G-6}$$

This is a rather remarkable result. It indicates that, for a given bandwidth, the total required power is independent of the number of beams (hence antenna gain and size) and depends on the frequency reuse factor only. Of course it is always less than or equal to that for single beam operation. It should be noted that the frequency reuse itself depends on the C/I requirement and the number of beams. In turn the required C/I is a function of the power per channel. Thus, in practice, a rather complicated relationship between various parameters of the system exists which must be carefully evaluated. Combining Eqs. (G-4) and (G-6) we obtain

$$\frac{P_N}{M_N} = \frac{1}{N} \left(\frac{P}{M}\right) \tag{G-7a}$$

or

$$\left(\frac{M_N}{M}\right) / \left(\frac{P_N}{P}\right) = N \tag{G-7b}$$

Eq. (G-7a) clearly shows the required power per channel decreases by a factor of N (the number of beams) independent of the frequency reuse factor r.

Eq. (G-7b) presents the obvious fact that for a given number of beams, an increase/decrease in channel capacity is accompanied by a linear increase/decrease in the total power, and is accomplished by increasing/decreasing the reuse factor. Table I presents some examples.

Table I. Total channel capacity and power requirement in an N-beam system. (M and P are the number of channels and total power, respectively, in a single beam system)

Reuse Factor, r	Total Number of Channels, $M_N = rNM$	Total Power, $P_N = rP$
1/N (minimum)	M	P/N
1/7	(N/7)M	P/7 (-8.5 dB)
1/4	(N/4)M	P/4 (-6.0 dB)
1 (maximum)	NM	P

In summary and conclusion, the total channel capacity and power requirements of a multibeam system are given by Eqs. (G-4), (G-6), and (G-7). Based on these results, the cochannel interference is not the only determinant in the selection of the reuse factor, and requirements of total power and channel capacity should also be considered. The analysis applies to both frequency and time division multiplexing systems.

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. JPL 85-58	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Second-Generation Mobile Satellite System A Conceptual Design and Trade-Off Study		5. Report Date June 1, 1985
		6. Performing Organization Code
7. Author(s) M.K. Sue and Y.H. Park		8. Performing Organization Report No.
9. Performing Organization Name and Address JET PROPULSION LABORATORY California Institute of Technology 4800 Oak Grove Drive Pasadena, California 91109		10. Work Unit No.
		11. Contract or Grant No. NAS7-918
		13. Type of Report and Period Covered JPL Publication
12. Sponsoring Agency Name and Address NATIONAL AERONAUTICS AND SPACE ADMINISTRATION Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract In recent years, interest has grown in the mobile satellite (MSAT) system, a satellite-based communications system capable of providing integrated voice and data services to a large number of users. To maintain its leadership in space, NASA is interested in promoting the development of a commercial mobile satellite system (MSS). Under a program called MSAT-X, NASA is developing advanced ground technology and techniques for future MSS's. To explore the potential of the MSS beyond the horizon of the first generation, using technologies of the 1990's, and to assist MSAT-X in directing its efforts, a conceptual design has been performed for a second-generation system to be launched around the mid-1990's. The design goal is to maximize the number of satellite channels and/or minimize the overall life-cycle cost, subject to the constraint of utilizing a commercial satellite bus with minimum modifications. To provide an optimal design, a series of trade-offs are performed, including antenna sizing, feed configurations, and interference analysis. Interference is a serious problem for MSAT and often an overlapping feed design is required to reduce interbeam interference. The trade-off studies will show that a simple non-overlapping feed is sufficient for the second-generation system, thus avoiding the need for the complicated beam-forming network that is associated with the overlapping feed designs. In addition, a system that operates at L-band, an alternative frequency band that is being considered by some for possible MSAT applications, is also presented.

17. Key Words (Selected by Author(s)) Spacecraft Design, Testing, and Performance Communications		18. Distribution Statement Unlimited/Unclassified	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price